Geochemistry Geophysics Geosystems G3

Article
Volume 14, Number 11
15 November 2013
doi: 10.1002/ggge.20285
ISSN: 1525-2027

Published by AGU and the Geochemical Society

Temporal geochemical variations in lavas from Kīlauea's Pu'u 'Ō'ō eruption (1983–2010): Cyclic variations from melting of source heterogeneities

Andrew R. Greene
Department of Natural Sciences, Hawai'i Pacific University, 45-045 Kamehameha Hwy, Kāne'ohe, Hawaii, 96744, USA (agreene@hpu.edu)

Michael O. Garcia
Department of Geology and Geophysics, University of Hawai'i, Honolulu, Hawaii, USA

Aaron J. Pietruszka
Department of Geological Sciences, San Diego State University, San Diego, California, USA

Now at U. S. Geological Survey, Denver Federal Center, Denver, Colorado, USA

Dominique Weis
Pacific Centre for Isotopic and Geochemical Research, Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, British Columbia, Canada

Jared P. Marske
Department of Terrestrial Magnetism, Carnegie Institution, Washington, D.C., USA

Michael J. Vollinger
Ronald B. Gilmore XRF Lab, Department of Geosciences, University of Massachusetts, Amherst, Massachusetts, USA

John Eiler
Planetary and Geological Sciences Institute, California Institute of Technology, Pasadena, California, USA

[1] Geochemical time series analysis of lavas from Kīlauea's ongoing Pu'u 'Ō'ō eruption chronicle mantle and crustal processes during a single, prolonged (1983 to present) magmatic event, which has shown nearly two-fold variation in lava effusion rates. Here we present an update of our ongoing monitoring of the geochemical variations of Pu'u 'Ō'ō lavas for the entire eruption through 2010. Oxygen isotope measurements on Pu'u 'Ō'ō lavas show a remarkable range ($\delta^{18}O$ values of 4.6–5.6‰), which are interpreted to reflect moderate levels of oxygen isotope exchange with or crustal contamination by hydrothermally altered Kīlauea lavas, probably in the shallow reservoir under the Pu'u 'Ō'ō vent. This process has not measurably affected ratios of radiogenic isotope or incompatible trace elements, which are thought to vary due to mantle-derived changes in the composition of the parental magma delivered to the volcano. High-precision Pb and Sr isotopic measurements were performed on lavas erupted at ~6 month intervals since 1983 to provide insights about melting dynamics and the compositional structure of the Hawaiian plume. The new results show systematic variations of Pb and Sr isotope ratios that continued the long-term compositional trend for Kīlauea until ~1990. Afterward, Pb isotope ratios show two cycles with ~10 year periods, whereas the Sr isotope ratios continued to increase until ~2003 and then shifted toward slightly less radiogenic values. The short-term periodicity of Pb isotope ratios may reflect melt extraction from mantle with a fine-scale pattern of repeating source heterogeneities or strands, which are about 1–3 km in diameter. Over the last 30 years, Pu'u 'Ō'ō lavas show 15% and 25% of the

known isotopic variation for Kīlauea and Mauna Kea, respectively. This observation illustrates that the dominant time scale of mantle-derived compositional variation for Hawaiian lavas is years to decades.

Components: 13,235 words, 12 figures, 2 tables.

Keywords: Hawaiian plume; tholeiitic volcanism; melt extraction; oceanic island.

Index Terms: 3619 Magma genesis and partial melting: Mineralogy and Petrology; 3621 Mantle processes: Mineralogy and Petrology; 1025 Composition of the mantle: Geochemistry; 1037 Magma genesis and partial melting: Geochemistry; 1038 Mantle processes: Geochemistry.

Received 5 March 2013; **Revised** 9 September 2013; **Accepted** 7 October 2013; **Published** 15 November 2013.

Greene, A. R., M. O. Garcia, A. J. Pietruszka, D. Weis, J. P. Marske, M. J. Vollinger, and J. Eiler (2013), Temporal geochemical variations in lavas from Kīlauea's Pu'u 'Ō'ō eruption (1983–2010): Cyclic variations from melting of source heterogeneities, *Geochem. Geophys. Geosyst.*, *14*, 4849–4873, doi:10.1002/ggge.20285.

1. Introduction

[2] Kīlauea, on the Island of Hawai'i (Figure 1), is one of the most active and best-monitored volcanoes in the world [*Heliker and Mattox*, 2003; *Wolfe et al*., 1987]. The ongoing Pu'u 'Ō'ō eruption on Kīlauea's East Rift Zone (Figure 1) has been active nearly continuously for 30 years and is Hawai'i's longest and most voluminous (~4 km^3) historical eruption [*Poland et al*., 2012]. The continuous petrologic and geochemical monitoring of the Pu'u 'Ō'ō eruption [e.g., *Garcia et al*., 2000; *Marske et al*., 2008; *Thornber*, 2003] has allowed us to witness the dynamic changes in the melting process and mantle source composition during a single, long-lasting magmatic event. Extraction and transport of melt through open channels during the Pu'u 'Ō'ō eruption has efficiently transmitted variations of melting in the heterogeneous source to lavas erupted at the surface without significant pooling and homogenization, preserving short-term isotopic and geochemical variations [*Pietruszka et al*., 2006].

[3] The long-term geochemical variations (many thousands of years) of Hawaiian and other ocean island basalts has been well documented due to detailed geochemical work on 3+ km deep drill core [e.g., *Albarède et al*., 1997; *Blichert-Toft et al*., 2003; *Bryce et al*., 2005; *Caroff et al*., 1995; *Rhodes et al*., 2012]. These studies chronicle processes on millennium time scales but miss potential short-term variations (<100 years), which may provide better insights into melting and crustal processes. Kīlauea's historical (1823–1982) and prehistoric (AD 900–1400) summit lavas reveal rapid and systematic changes in Pb, Sr, Nd, O, and U-series isotope ratios on a time scale of decades to centuries [*Garcia et al*., 2003, 2008; *Marske et al*., 2007; *Pietruszka and Garcia*, 1999; *Pietruszka et al*., 2001]. The Pu'u 'Ō'ō eruption (sampled from hourly to monthly) shows compositional change over hours (in rare cases) for major elements to a few years for isotope ratios [*Garcia et al*., 2000; *Marske et al*., 2008]. The long duration and vigorous activity (~0.35×10^6 m^3 of lava erupted daily) of Pu'u 'Ō'ō [e.g., *Sutton et al*., 2003] provides a rare opportunity to look beyond the shallow-level crustal processes associated with the short eruptions (days to weeks) that typify many active basaltic volcanoes (e.g., Mauna Loa, Etna, Piton de la Fournaise, Karthala, Grimsvötn) and into the mantle. In addition, Pu'u 'Ō'ō magmas may partially bypass Kīlauea's summit reservoir (2–6 km depth beneath the summit caldera) on their way to the East Rift Zone, and mostly avoid its buffering effects [*Garcia et al*., 2000]. Therefore the Pu'u 'Ō'ō eruption is one of Earth's best probes for sampling mantle-derived melts almost continuously over nearly three decades.

[4] The study of isotopic and geochemical variation in magmatic events over short time scales (months to years) in oceanic island lavas improves our temporal and spatial resolution of melting processes and the chemical structure of mantle plumes [*Abouchami et al*., 2000; *Eisele et al*., 2003; *Hofmann et al*., 1984; *Vlastélic et al*., 2005]. Recent studies of Pb, Sr, and Nd isotope ratios for part of the Pu'u 'Ō'ō eruption [*Marske et al*., 2008] and other active basaltic volcanoes [e.g., Piton de la Fournaise; *Vlastélic et al*., 2005] detected rapid and systematic changes over short

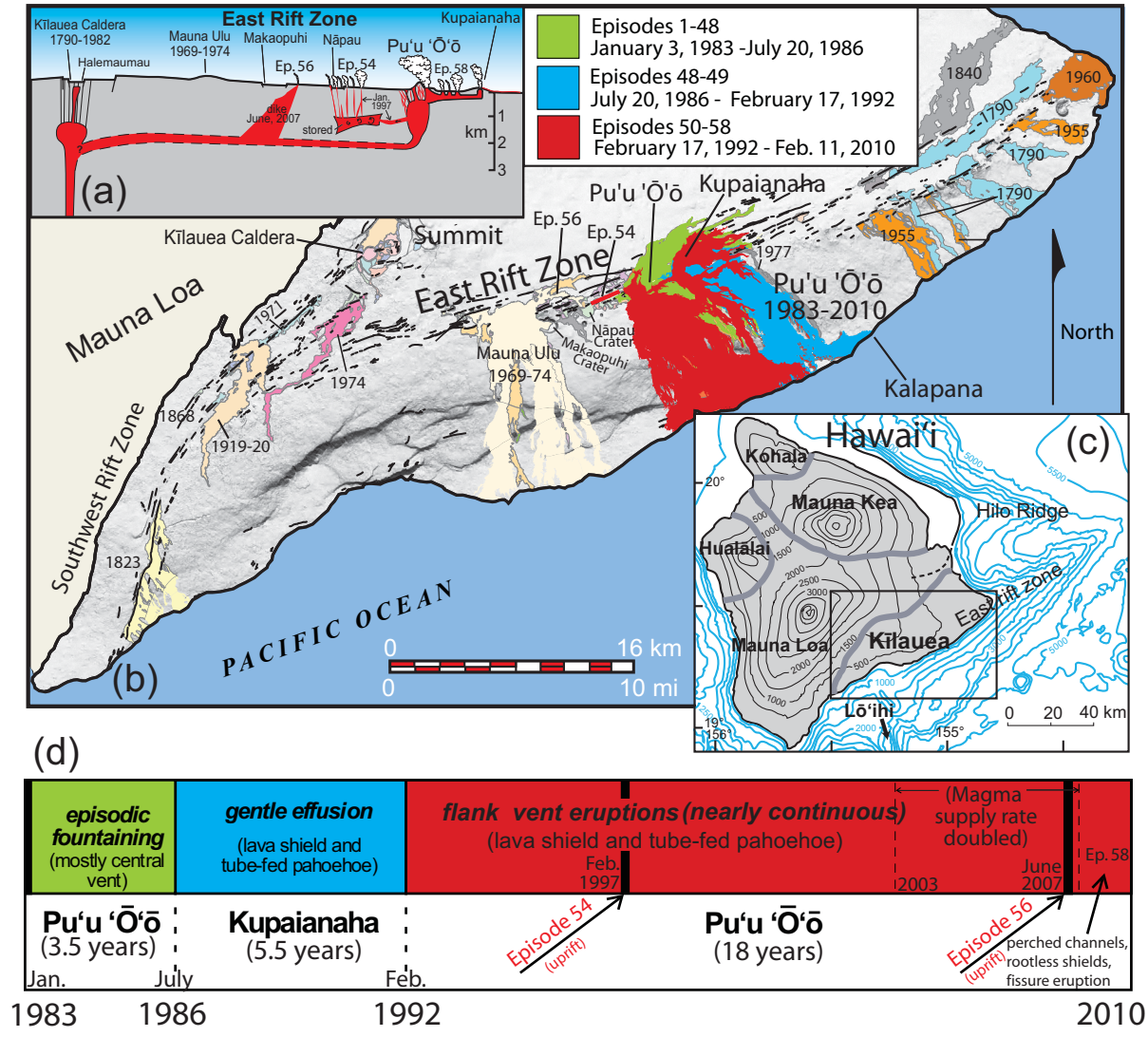

Figure 1. Map of flow fields from the Pu'u 'Ō'ō-Kupaianaha eruption on the East Rift Zone of Kīlauea Volcano from 1983 to 2010 and historical flows, with a timeline summarizing the predominant style of eruptive activity. (a) A schematic cross section of summit and East Rift Zone shows the proposed magmatic plumbing system for Kīlauea Volcano, with locations for episodes 54 and 56 uprift of Pu'u 'Ō'ō. Mantle-derived magma for this eruption is thought to partially bypass the summit reservoir based on the rapid changes in lava composition [*Garcia et al*., 1996]. (b) Map of Kīlauea East Rift Zone with flow fields from intervals of the Pu'u 'Ō'ō eruption. Legend shows episodes in each interval of eruptive activity. Map provided by USGS Hawaiian Volcano Observatory. (c) Map of the island of Hawai'i with area of map in Figure 1b indicated with box. (d) Timeline of the Pu'u 'Ō'ō eruption. Episode 54 was a fissure eruption in and downrift of Nāpau Crater that occurred over 23 h in January 1997, following the collapse of the Pu'u 'Ō'ō cone. Episode 56 was a brief (<1 day) fissure eruption northeast of Makaopuhi Crater (uprift of Pu'u 'Ō'ō) that occurred in June 2007, coinciding with an intrusion and collapse of Pu'u 'Ō'ō crater floor. Dashed lines between 2003 and 2007 indicate period when magma supply rate nearly doubled [*Poland et al*., 2012].

time scales (years to decades) resulting from source heterogeneity, and variations in crustal processes. Here we present new high-precision Pb, Sr, and O isotope ratios, and major- and trace-element abundances for Pu'u 'Ō'ō lavas erupted between January 1983 and June 2010. These data

are combined with previously published high-precision isotope and trace-element data from 1998 to 2005 Pu'u 'Ō'ō lavas [*Marske et al*., 2008]. The new Pb and Sr isotope and inductively coupled plasma mass spectrometry (ICP-MS) data provide a record of isotopic and geochemical variation of Pu'u 'Ō'ō lavas at ~6 month intervals, whereas X-Ray fluorescence (XRF) data was collected at ~2 week intervals. This time series analysis of Pu'u 'Ō'ō lavas allows us to distinguish the changing roles of mantle and crustal processes in great detail. The new Pb and Sr isotope ratios are used to assess the short-term expression of mantle source components throughout the course of the eruption and to evaluate the effects on lava composition of recent doubling of the magma supply [2003–2007; *Poland et al*., 2012]. These results are compared to the longer-term variations for Kīlauea and other Hawaiian shield volcanoes.

2. Geologic Background of Kīlauea Volcano and the Pu'u 'Ō'ō Eruption (1983–2010)

[5] Kīlauea Volcano is currently in the middle of its shield-building stage [*DePaolo and Stolper*, 1996], erupting tholeiitic lava at a rate of ~0.13 km^3/yr [*Sutton et al*., 2003], one of the highest rates of any volcano on Earth. Kīlauea rises 1240 m above sea-level on the southern flank of its larger neighbor, Mauna Loa (4168 m; Figure 1). Geochemical evidence favors a deep mantle plume origin for Hawaiian magmas [e.g., *Kurz et al*., 1982; *Weis et al*., 2011]. Shield stage magmas are thought to originate from partial melting at mantle depths of 70–120 km within the upper Hawaiian plume [*Watson and McKenzie*, 1991]. Magmas are extracted from the upwelling mantle within the melting region and transported through chemically isolated channels towards the surface [*Pietruszka et al*., 2006]. These pooled melts ascend through the lithosphere via a primary conduit into a shallow (2–6 km) magmatic complex within Kīlauea [*Eaton and Murata*, 1960; *Ryan*, 1987; *Tilling and Dvorak*, 1993; *Wright*, 1971]. Kīlauea eruptions occur in and around its summit caldera and East and Southwest Rift Zones. Approximately 90% of the subaerial surface of Kīlauea Volcano is covered with tholeiitic lava less than 1100 years old [*Holcomb*, 1987]. Prior to 1955, historical (post-1820) eruptions on Kīlauea occurred mostly at or near the summit [*Macdonald et al*., 1983]. Subsequently, rift zone eruptions became more common, especially along the East Rift Zone, including the 1969–1974 Mauna Ulu eruption, the most voluminous historical eruption prior to Pu'u 'Ō'ō [*Macdonald et al*., 1983].

[6] The Pu'u 'Ō'ō-Kupaianaha eruption (referred to as the Pu'u 'Ō'ō eruption throughout this paper) began on 2 January 1983 with the intrusion of a dike within Kīlauea's East Rift Zone, although it was preceded by months of intrusions from the summit into the rift zone [*Wolfe et al*., 1987]. It was followed 24 h later by eruptive activity along a discontinuous 7 km long fissure, which localized to a central vent, Pu'u 'Ō'ō (Figure 1 and Table 1). The eruption can be categorized into three broad phases based on eruptive style and location: (1) 1983–1986: brief (mostly less than 24 h), episodic eruptions (24 day average repose between eruptions) with fountaining up to 400 m, mainly from the Pu'u 'Ō'ō vent [*Heliker and Mattox*, 2003]; (2) 1986–1992: nearly continuous effusion from the Kupaianaha vent, which was considered to have a shallow (<100 m deep) conduit connection with Pu'u 'Ō'ō, 3 km uprift [*Garcia et al*., 1996]; and (3) 1992–2010: nearly continuous effusion mostly from vents within, and on the southwest and east flanks of Pu'u 'Ō'ō, and from rootless shields ~2 km east of Pu'u 'Ō'ō [*Poland et al*., 2008]. This pattern was interrupted on 29 January 1997 (episode 54) by the ~150 m collapse of the crater floor inside the Pu'u 'Ō'ō cone, and propagation of eruptive fissures 4 km uprift (west) of Pu'u 'Ō'ō, which were active for less than a day [*Heliker and Mattox*, 2003]. This event was followed by a 6 week hiatus in effusive activity, although glow returned to the Pu'u 'Ō'ō vent on 24 February 1997 (Table 1). Afterward, and until June 2007, lava erupted nearly continuously from flank vents on Pu'u 'Ō'ō (episode 55). On 19 June 2007, a dike intrusion in the upper East Rift Zone resulted in a brief, small (1500 m^3) eruption (episode 56) ~6 km uprift from Pu'u 'Ō'ō [*Montgomery-Brown et al*., 2010], which was followed by a 2 week hiatus in effusion [*Poland et al*., 2008]. Lava production resumed for 3 weeks in and around Pu'u 'Ō'ō cone (episode 57) until 21 July 2007, when a fissure opened on the east flank of Pu'u 'Ō'ō and propagated eastward towards Kupaianaha (Figure 1 and Table 1). This marked the beginning of episode 58 [*Poland et al*., 2008], which continued through the end of 2010 mostly as tube-fed flows from a vent ~2 km east of Pu'u 'Ō'ō. The other notable Kīlauea eruptive activity during the Pu'u 'Ō'ō eruption is an ongoing summit eruption that started in March 2008 [*Johnson et al*., 2010].

Table 1. Summary of the Pu‘u ‘Ō‘ō Eruption[a]

Primary Vent	Episode	Episode Start Date	Repose Length (Days)	Episode Length	Volume (10^6 x m^3)	Eruption Rate (10^3 m^3/day)	Vent/Location	Brief Description
Pu‘u ‘Ō‘ō	1	3 Jan 1983	Start	20 days	14	—	Fissure 1; activity localized at Pu‘u Halulu and Pu‘u Kahaulea east of Pu‘u ‘Ō‘ō	Initial fissure opened in Napau Crater after seismic swarm propagated down ERZ; fissures extended 8 km; fissures localized to 1 km near Pu‘u Kahaulea; fountains from Pu‘u Halulu built a 60 m-high cone
Pu‘u ‘Ō‘ō	2–47	10 Feb 1983	8–65 (between episodes)	**~3.8 years**	371	~300	Mostly Pu‘u ‘Ō‘ō; Episodes 2–3 localized at Pu‘u Halulu and Pu‘u Kahaulea east of Pu‘u ‘Ō‘ō; Episode 4–47 Puu Oo primary vent	Episodic fire fountaining; episodes mostly <24 h long separated by an repose length average of 24 days; effusion rates increased though episode 39; maximum lava fountain of 470 m high; first year changed from low fountains and pahoehoe rivers to high fountains and ‘a‘a fans; fountain-fed ‘a‘a by episode 20; cone built 255 m high and 1.4 km in diameter; summit inflated between fountaining episodes and deflated during episodes
Kupaianaha	48	18 July 1986	24	**~5.5 years**	~500	~400–0.5	Kupaianaha; fissure 3 km east of Pu‘u ‘Ō‘ō	Fissures first opened at the base of Pu‘u ‘Ō‘ō and 22 h later opened 3 km downrift at a vent to be named Kupaianaha; 5.5 years of nearly continuous gentle effusion; large lava pond formed over vent (140 m × 300 m); broad lava shield formed and tube-fed pahoehoe was common way lava spread to coast; homes destroyed in town of Kalapana; lava tubes to sea mid-1987 to 1989; lava entered sea during ~68% of episode; lava active in Pu‘u ‘Ō‘ō crater during most of episode
Pu‘u ‘Ō‘ō	49	8 Nov 1991	None	18 days	11	0.6	Fissure 2 between Pu‘u ‘Ō‘ō and Kupaianaha	Fissures opened on Pu‘u ‘Ō‘ō and propagated to Kupaianaha; output waned during episode; gentle effusion, lava shield and tube-fed pahoehoe; fissure vents, pahoehoe
Pu‘u ‘Ō‘ō	50	17 Feb 1992	11	15 days	3	–	Pu‘u ‘Ō‘ō flank; radial fissure on west flank of Pu‘u ‘Ō‘ō cone	Eruption returned to Pu‘u ‘Ō‘ō; radial fissures on flank of cone; flank vent eruptions; lava shield banked up against the south and west Pu‘u ‘Ō‘ō cone; spatter cones formed over vents; mostly tube-fed pahoehoe; continuous quiet effusion
Pu‘u ‘Ō‘ō	51	7 Mar 1992	4	161 days	32	~300	Pu‘u ‘Ō‘ō flank	Flank vent eruptions; mostly tube-fed pahoehoe to the sea; continuous quiet effusion; lava shield banked up against the south and west Pu‘u ‘Ō‘ō cone
Pu‘u ‘Ō‘ō	52	3 Oct 1992	None	15 days	2	~300	Pu‘u ‘Ō‘ō flank	Flank vent eruptions; mostly tube-fed pahoehoe to the sea; continuous quiet effusion; lava shield banked up against the south and west Pu‘u ‘Ō‘ō cone
Pu‘u ‘Ō‘ō	53	20 Feb 1993	None	**~4 years**	~535	~300	Pu‘u ‘Ō‘ō flank	Flank vent eruptions; mostly tube-fed pahoehoe to the sea; continuous quiet effusion; lava shield banked up against the south and west Pu‘u ‘Ō‘ō cone; collapse pits formed on the side of Pu‘u ‘Ō‘ō
Pu‘u ‘Ō‘ō	54	29 Jan 1997	None	~1 day	0.3	0.3	Fissure 3; 2–4 km uprift of Pu‘u ‘Ō‘ō	(1) Lava lake inside the Pu‘u ‘Ō‘ō vent drained and crater floor dropped 150 m; (2) Pu‘u ‘Ō‘ō west flank collapsed; 115 m gap in west side of Pu‘u ‘Ō‘ō; (3) fissure 4 km erupted uprift for 1 day, in and downrift of Napau Crater, followed by longest eruptive hiatus since 1987 (24 days); distinct lava chemistry involved magma mixing with differentiated magma stored in rift zone

Table 1. (continued)

Primary Vent	Episode	Episode Start Date	Repose Length (Days)	Episode Length	Volume (10^6 x m^3)	Eruption Rate (10^3 m^3/day)	Vent/Location	Brief Description
Pu‘u ‘Ō‘ō	55	24 Feb 1997	24	**10 years**	~265	200–500	Pu‘u ‘Ō‘ō and its flank	Lava spilled from crater to form new pond; lava spilled from crater a month later; new flank vent eruptions west and southwest of cone; spatter cones on flanks crusted over to produce mostly tube-fed pahoehoe; by June 1997 lava overtopped the gap in wall of Pu‘u ‘Ō‘ō and flowed from crater for first time in 11 years; flank vents undermined Pu‘u ‘Ō‘ō cone in December, 1997; Puka Nui collapse pit formed on southwest flank of cone; 31 pauses occurred during episode 55
Pu‘u ‘Ō‘ō	56	19 June 2007	None	~6 h	0.00145	0.00036	250 m long fissure in the forest northeast of Kane Nui o Hamo, approximately 6 km west of Pu‘u ‘Ō‘ō	Father’s Day eruption near Kane Nui o Hamo north of Makaopuhi Crater; magma supply to Pu‘u ‘Ō‘ō was cut off on 17 June 2007; earthquake swarms indicated magma movement in the upper ERZ; spatter erupted from fissure in forested area; small lava flow (200 m × 50 m) accompanied intrusion in ERZ; crater floor in Pu‘u ‘Ō‘ō collapsed and eruption shut off
Pu‘u ‘Ō‘ō	57	1 July 2007	19 days	None	0.82–1.23	~65	Pu‘u ‘Ō‘ō crater	After about two-weeks of quiet, the eruption began again on 1 July. Lava began to refill the crater. On 8 July, effusion waned as the crater began to uplift in a piston-like fashion. The crater then began to fill and reached to within 30 m of the eastern rim of Pu‘u ‘Ō‘ō crater by mid-July.
Pu‘u ‘Ō‘ō	58	21 July 2007	None	**~4 years** ended 7 March 2011	~320 (as of the end of 2009)		From fissure east of P u‘u ‘Ō‘ō crater	Perched lava channel, rootless shields; for the first time since 7 February 1992, lava begins erupting east of Pu‘u ‘Ō‘ō crater. Thanksgiving Eve breakout, lava bypasses 21 July 2007 channel and erupts on channel flank; 5 March 2008 ocean entry active for the first time since June 2007; explosion in Halema‘uma‘u Crater at summit on 19 March 2008; June 2008 spattering vents and a small pond of lava in Pu‘u ‘Ō ‘ō, lava fountains gush from the TEB tube system, channelized ’a’ā flows in Royal Gardens, and large littoral explosions at Kīlauea’s ocean entry near Kalapana; Waikupanaha ocean entry active through much of 2009, and occasionally Kupapa’u ocean entry to west

[a]Repose length refers to duration of pause between eruptive episodes. Episode identifies occurrences of fountaining or lava flow separated by quiescent periods. Volume is dense rock equivalent (DRE) erupted during each episode. Data sources: *Garcia et al*. [2000] and references therein, *Wolfe et al*. [1998], *Heliker and Mattox* [2003].

Geochemistry Geophysics Geosystems G3

10.1002/ggge.20285

3. Description of Samples and Analyses Performed in This Study

[7] This study presents 52 new high-precision Pb and Sr isotope analyses (from 1983 to 1997 and 2006 to 2010), 11 new O isotope analyses (from after 1997; Table 2), and 13 new ICP-MS trace-element analyses of Pu'u 'Ō'ō lava samples (mostly after 2005; data and analytical methods are presented in the supporting information).[1] New XRF major- and trace-element analyses for 52 Pu'u 'Ō'ō lavas erupted from 2006 to 2010 are also presented. In addition, new XRF trace-element analyses are given for samples erupted prior to 1998, when a new, more precise XRF instrument became available. Almost all of the samples in this study were collected in a molten state and quenched with water to minimize post-eruption crystallization. The sample names are the date that each lava sample was collected (e.g., day-month-year), which is generally within a day of its eruption when lava is flowing in open channels on the surface or in lava tubes [e.g., *Garcia et al*., 2000] or up to a week or more when it is oozing within slowly advancing pahoehoe flows [K. Ho, personal communication, 2013]. Descriptions of the petrography of typical Pu'u 'Ō'ō lavas can be found in *Garcia et al*. [1989, 1992, 1996, 2000] and *Marske et al*. [2008]. Fourteen high-precision Pb and Sr isotope ratios for Pu'u 'Ō'ō lavas erupted from 1998 to 2005 from *Marske et al*. [2008] and 15 O isotope analyses from *Garcia et al*. [1998] are listed in Table 2 and are included in plots for completeness.

4. Temporal Geochemical Variations in Lavas From 1983 to 2010

[9] Early Pu'u 'Ō'ō lavas (1983 to early 1985) record rapid (hours to days) variations in major and compatible trace-element abundances (Figure 2; Supporting information). These lavas show petrographic evidence for both crystal fractionation and magma mixing [*Wolfe et al*., 1987; *Garcia et al*., 1992]. Crystal fractionation of olivine (with minor clinopyroxene and plagioclase, especially for 1983 lavas) is the dominant process controlling short-term major-element variation in Pu'u 'Ō'ō lavas [*Garcia et al*., 1992]. To remove the effects of crystal fractionation on parental magma compositions, major-element abundances of lavas containing only olivine (MgO >7.0 wt %) were normalized to 10 wt % MgO by the addition of equilibrium composition olivine (98.5%) and spinel (1.5%) in 0.5 mol % steps, as described by *Garcia et al*. [2003]. The increases in MgO, CaO/Al_2O_3, and CaO/TiO_2 and decreases in MgO-normalized incompatible element abundances (e.g., TiO_2, K_2O) between 1983 and early 1985 (Figure 2) reflect mixing of new high-MgO magma with decreasing amounts of a hybrid magma formed at the start of the eruption by mixing two differentiated, rift-zone stored magmas [*Garcia et al*., 1989, 1992]. Lavas erupted after early 1985 show no petrographic or geochemical evidence for mixing [*Shamberger and Garcia*, 2007] until the 1997 uprift eruption, which is discussed below.

[10] From 1985 to 1994, Pu'u 'Ō'ō lavas show a wide range in MgO reflecting the periodic hiatuses in eruptive activity [*Garcia et al*., 1992], and gradual changes in MgO-normalized concentrations of major elements (TiO_2 and K_2O), and ratios of major (e.g., CaO/Al_2O_3; Figure 2) and trace elements (Nb/Y; Figure 3). In 1994, lavas began a period of increasing MgO-normalized SiO_2 and overall decreasing MgO-normalized TiO_2 that persisted until 2001. Other geochemical parameters continued their long-term trends (e.g., decreasing CaO/Al_2O_3, MgO-normalized K_2O, and Nb/Y, and increasing Zr/Nb; Figures 2 and 3). Starting in mid- to late 2003, there was an increase in lava production with effusion rates doubling in 2005 [*Poland et al*., 2012]. The lava MgO content decreased from 2003 to 2007 and was relatively low (<7.5 wt %, mostly <7.2 wt %) with limited variation (Figure 2). This decrease continued the overall trend of decreasing MgO that started in ~1998, as noted by *Poland et al*. [2012]. There is also a decrease in MgO-normalized SiO_2 and an increase in MgO-normalized TiO_2 and K_2O during 2003–2007 (Figures 2 and 3). Lava MgO increased from 2008 to 2009 as did CaO/TiO_2 and values of MgO-normalized SiO_2, although MgO and SiO_2 values dropped afterwards for the most recently erupted samples that were analyzed in this study (Figure 2). For more on major- and trace-element variations in 1983–2005 Pu'u 'Ō'ō lavas, see *Garcia et al*. [1989, 1992, 1996, 2000], *Marske et al*. [2008], and *Thornber* [2003].

[11] The brief eruptive outbreaks uprift of the Pu'u 'Ō'ō vent in 1997 (~3 km uprift for episode 54) and 2007 (~6 km uprift for episode 56; Figure 1)

[1] Additional supporting information may be found in the online version of this article.

Table 2. Pb, Sr and O Isotopic Geochemistry of Pu‘u ‘Ō‘ō Lavas from 1983–2010[a]

Sample		$^{206}Pb/^{204}Pb$	2σ	$^{207}Pb/^{204}Pb$	2σ	$^{208}Pb/^{204}Pb$	2σ	$^{87}Sr/^{86}Sr$	2σ	$\delta^{18}O$	1σ
23 Jan 1983	°	18.5247	0.0009	15.4800	0.0008	38.155	0.0020	0.703590	0.000009	4.56	0.02
9 Apr 1983		18.5309	0.0007	15.4893	0.0007	38.165	0.0017	0.703573	0.000008		
3 July 1983	°	18.4780	0.0007	15.4765	0.0008	38.117	0.0017	0.703573	0.000007	4.77	0.03
31 Jan 1984		18.4595	0.0009	15.4765	0.0007	38.103	0.0020	0.703587	0.000008		
12 Sep 1984		18.4417	0.0008	15.4747	0.0007	38.091	0.0019	0.703555	0.000009		
8 Feb 1985	°	18.4342	0.0010	15.4743	0.0009	38.087	0.0024	0.703567	0.000008	4.76	0.05
21 Apr 1985	°									4.82	0.10
30 Jul 1985		18.4306	0.0007	15.4756	0.0007	38.089	0.0020	0.703571	0.000008		
2 Jun 1986	°	18.4138	0.0009	15.4755	0.0008	38.079	0.0020	0.703580	0.000009	4.94	0.30
26 Jun 1986	°									4.77	0.02
13 Sep 1986	°	18.4138	0.0008	15.4726	0.0007	38.074	0.0020	0.703590	0.000008	5.17	0.01
16 Mar 1987	°	18.4108	0.0006	15.4717	0.0005	38.069	0.0014	0.703589	0.000009	5.25	0.02
18 Oct 1987		18.3992	0.0008	15.4746	0.0008	38.068	0.0022	0.703597	0.000009		
19 Jan 1988		18.3952	0.0006	15.4715	0.0006	38.061	0.0016	0.703577	0.000008		
18 Aug 1988		18.3871	0.0008	15.4703	0.0007	38.052	0.0017	0.703583	0.000009		
26 Mar 1989	°	18.3882	0.0007	15.4717	0.0007	38.055	0.0019	0.703584	0.000009	5.11	0.05
7 Jul 1989		18.3861	0.0010	15.4725	0.0009	38.054	0.0022	0.703581	0.000009		
7 Jul 1989	†	18.3851	0.0009	15.4710	0.0008	38.052	0.0021	0.703576	0.000009		
7 Jan 1990	°	18.3881	0.0009	15.4745	0.0008	38.056	0.0018	0.703584	0.000008	5.03	0.01
27 May 1990		18.3864	0.0008	15.4716	0.0007	38.054	0.0020	0.703603	0.000007		
21 Oct 1990		18.3856	0.0007	15.4693	0.0006	38.049	0.0017	0.703597	0.000008		
12 May 1991	°	18.3992	0.0009	15.4739	0.0007	38.063	0.0019	0.703581	0.000008	5.08	0.04
1 Aug 1991	°									5.11	0.04
6 Jun 1992	°	18.4048	0.0009	15.4721	0.0009	38.061	0.0019	0.703585	0.000008	5.04	0.10
13 Aug 1993	°	18.4112	0.0007	15.4752	0.0006	38.072	0.0015	0.703611	0.000008	4.98	0.07
4 Jan 1994		18.4098	0.0009	15.4736	0.0008	38.067	0.0020	0.703607	0.000008		
25 Apr 1994	°	18.4100	0.0009	15.4737	0.0009	38.068	0.0027	0.703586	0.000008	5.01	0.02
9 Oct 1994		18.4059	0.0008	15.4718	0.0007	38.066	0.0019	0.703598	0.000007		
27 Apr 1995	°	18.4059	0.0009	15.4721	0.0008	38.066	0.0023	0.703604	0.000009	5.25	0.05
14 Oct 1995		18.4068	0.0008	15.4729	0.0008	38.071	0.0021	0.703602	0.000009		
19 Jan 1996	°									5.19	0.07
15 Mar 1996		18.4064	0.0010	15.4738	0.0008	38.070	0.0023	0.703592	0.000009		
22 Aug 1996		18.4038	0.0009	15.4722	0.0008	38.065	0.0016	0.703612	0.000007		
10 Jan 1997	°	18.4010	0.0012	15.4728	0.0011	38.064	0.0019	0.703606	0.000009	5.2	0.05
23 Jul 1997		18.3993	0.0010	15.4729	0.0010	38.068	0.0025	0.703601	0.000007		
10 Jan 1998		18.3958	0.0007	15.4728	0.0006	38.067	0.0014	0.703591	0.000008		
10 Jan 1998	†	18.3940	0.0007	15.4711	0.0006	38.063	0.0016	0.703593	0.000007		
11 May 1998		18.4005	0.0009	15.4740	0.0008	38.071	0.0020	0.703605	0.000010		
7 Sep 1998		18.4082	0.0008	15.4775	0.0006	38.083	0.0017	0.703601	0.000006	5.33	0.06
7 Sep 1998	*†	18.4107	0.0004	15.4727	0.0005	38.075	0.0012			5.29	0.08
13 Feb 1999		18.4068	0.0010	15.4783	0.0008	38.085	0.0021	0.703607	0.000006		
13 Feb 1999	*†	18.4124	0.0004	15.4736	0.0004	38.076	0.0011				
19 Jun 1999		18.3987	0.0010	15.4805	0.0007	38.085	0.0020	0.703620	0.000009		
27 Oct 1999	*	18.4018	0.0004	15.4726	0.0004	38.069	0.0011	0.703622	0.000009	5.36	0.08
19 Feb 2000	*	18.4072	0.0004	15.4712	0.0004	38.072	0.0011	0.703624	0.000007		
21 Jun 2000	*	18.4067	0.0004	15.4704	0.0004	38.069	0.0011	0.703638	0.000007	5.28	0.08
8 Jan 2001	*	18.4116	0.0004	15.4721	0.0004	38.074	0.0011	0.703627	0.000012	5.31	0.08
7 Jul 2001	*	18.4137	0.0004	15.4719	0.0004	38.073	0.0013	0.703626	0.000009		
9 Feb 2002	*	18.4139	0.0004	15.4707	0.0004	38.069	0.0011	0.703637	0.000008		
20 Aug 2002	*	18.4152	0.0004	15.4722	0.0004	38.072	0.0011	0.703639	0.000005		
12 Apr 2003	*	18.4161	0.0005	15.4726	0.0005	38.072	0.0013	0.703641	0.000005	5.31	0.08
15 Jan 2004	*	18.4154	0.0005	15.4719	0.0005	38.069	0.0012	0.703632	0.000007	5.21	0.08
7 Jun 2004	*	18.4146	0.0003	15.4716	0.0004	38.068	0.0010	0.703624	0.000007		
31 Jan 2005	*	18.4170	0.0005	15.4735	0.0006	38.075	0.0012	0.703624	0.000005	4.96	0.13
8 Aug 2005	*	18.4119	0.0005	15.4727	0.0005	38.070	0.0013	0.703622	0.000010		
29 Jan 2006	*	18.4087	0.0004	15.4720	0.0004	38.065	0.0012	0.703623	0.000009		
24 Jun 2006	†	18.4062	0.0028	15.4724	0.0026	38.066	0.0059	0.703612	0.000008	5.23	0.03
24 Jun 2006	*	18.4073	0.0016	15.4714	0.0018	38.063	0.0060	0.703617	0.000013	5.23	0.03
6 Apr 2007	*	18.4065	0.0003	15.4715	0.0003	38.063	0.0009	0.703617	0.000007	5.35	0.13
17 Jun 2007	*	18.4019	0.0004	15.4709	0.0004	38.062	0.0012	0.703626	0.000006	5.63	0.13
22 Mar 2008	*	18.4038	0.0003	15.4700	0.0003	38.061	0.0010	0.703607	0.000008	5.45	0.13
2 May 2008	*	18.4045	0.0003	15.4721	0.0004	38.066	0.0010	0.703609	0.000009		
15 Nov 2008		18.3972	0.0009	15.4704	0.0007	38.058	0.0024	0.703600	0.000008		
29 Jan 2009	*	18.4003	0.0005	15.4709	0.0006	38.061	0.0012	0.703628	0.000008		
7 May 2009		18.4005	0.0008	15.4736	0.0007	38.066	0.0020	0.703624	0.000010		
4 Jun 2009	*	18.4009	0.0003	15.4720	0.0004	38.064	0.0010	0.703610	0.000007		
16 Oct 2009	*	18.3994	0.0005	15.4714	0.0006	38.062	0.0012	0.703622	0.000007		
22 Jan 2010	*	18.3987	0.0005	15.4708	0.0005	38.060	0.0013	0.703617	0.000007		

[a]* indicates analysis at San Diego State University (SDSU), analyses from 7 Sep 1998 to 8 Aug 2005 are from *Marske et al*. [2008]. Sr isotope analyses from 1983–1997 and 2006–2010 were performed at PCIGR. † Chemistry duplicate. ° Published δ18O analyses from *Garcia et al*. [1998]. Analytical methods are described in the supporting information. 24 Jun 2006 is an in-house glass standard called Menehune collected from a Pu‘u ‘Ō‘ō lava flow (errors are the external ±2s of the replicate analyses; average of four analyses for Pb and Sr at PCIGR; 68 for Pb and 26 for Sr at SDSU). US Geological Survey sample numbers for lavas between up to16 Mar 87 are 23 Jan 1983: 1–054, 9 April 1983: 3–117, 3 Jul 1983: 5–139, 31 Jan 1984: 14–232, 12 Sep 1984: KE24–25 310S, 8 Feb 1985: 30–362, 30 Jul 1985: 35–419, 1 Jan 1986:40–484, 2 Jun 1986: 46–536, 13 Sep 1986: 48–649, 16 Mar 1987: 48–714F.

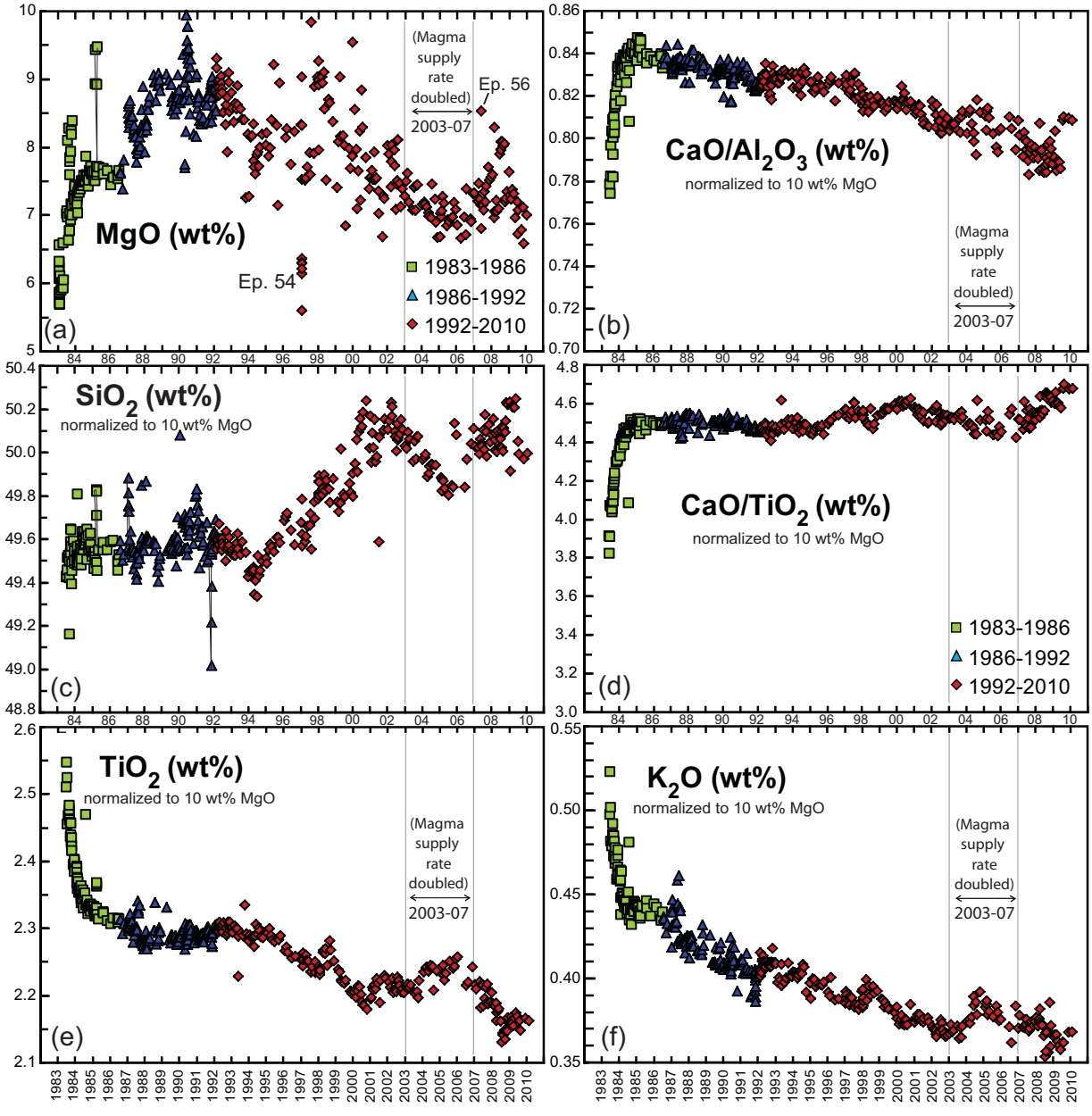

Figure 2. Major-element variation diagrams for Pu'u 'Ō'ō lavas from 1983 to 2010. All major elements and ratios except MgO were normalized to 10 wt % MgO [the most primitive lava erupted from Pu'u 'Ō'ō; *Garcia et al*., 2000] by addition of equilibrium composition olivine (98.5%) and spinel (1.5%) in 0.5 mol % steps [*Garcia et al*., 2003; *Rhodes and Vollinger*, 2004]. Pu'u 'Ō'ō lavas with <7.2 wt % MgO may have crystallized minerals other than olivine (e.g., clinopyroxene and plagioclase) and were not included in the olivine normalization procedure and are not shown in all the plots, except MgO. Episode 54 (Ep. 54; 29–30 January 1997) lavas involved mixing of evolved magmas stored in the rift zone and MgO-rich magma. Three intervals of eruptive activity in legend and colors correspond with those shown in Figure 1. CaO/TiO_2 and CaO/Al_2O_3 ratios also use normalized data although are virtually unaffected by olivine fractionation. Vertical lines indicate nearly double magma supply rate between 2003 and 2007 [*Poland et al*., 2012]. Data are presented in the supporting information. Uncertainty for analyses is described in the supporting information.

occurred after major collapses of the Pu'u 'Ō'ō crater floor (Table 1). The lavas erupted from these uprift vents were geochemically distinct. Compared to coeval Pu'u 'Ō'ō vent lavas, those from episode 54 have lower MgO (5.6–6.4 versus 7.5–10.1 wt %), CaO/TiO_2 (2.8–3.4 versus 4.4), Sr/Nb and Zr/Nb ratios (Figure 3). These geochemical signatures and the petrographic evidence of

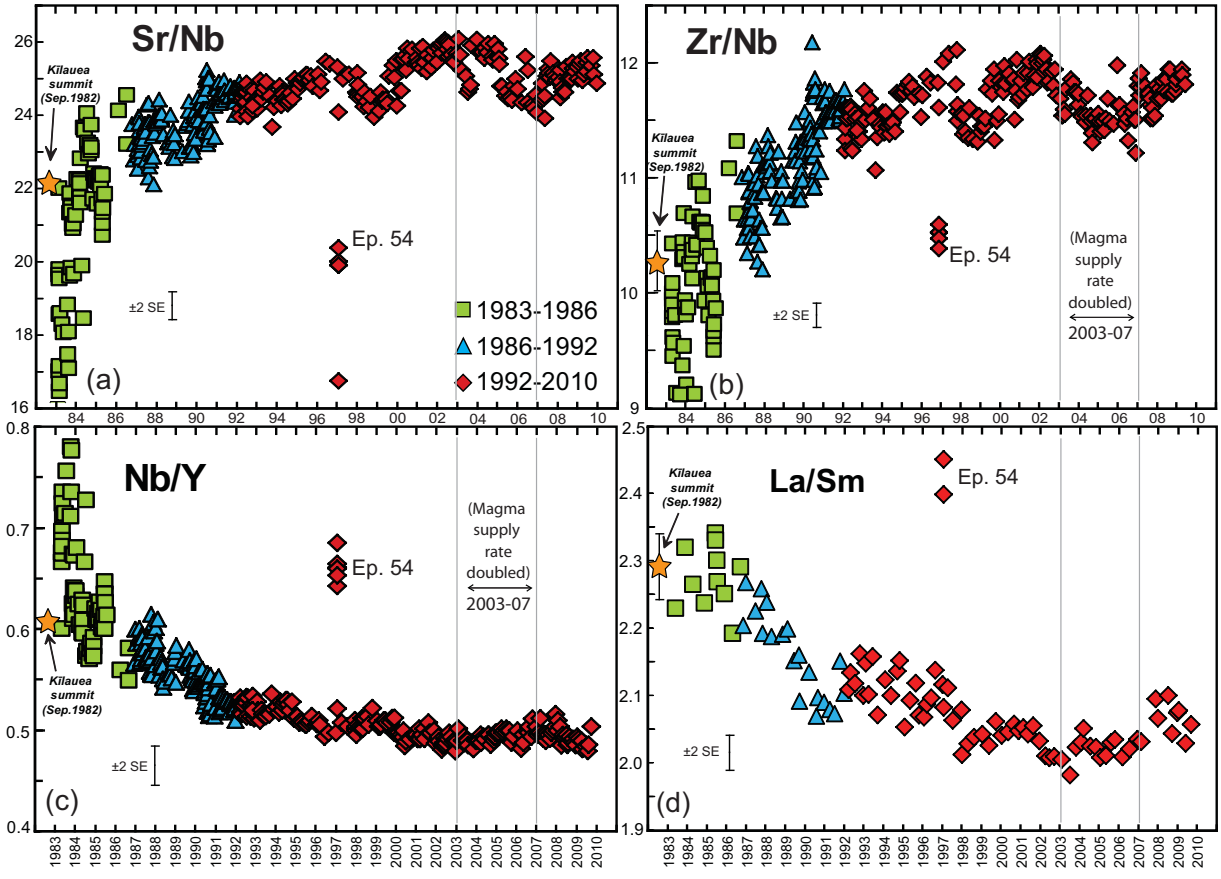

Figure 3. Trace-element ratios versus time for Pu'u 'Ō'ō lavas from 1983 to 2010. Overall exponential variation in trace-element ratios indicates progressive depletion of the source. In the La/Sm versus time plot, a subset of samples analyzed at PCIGR (April 1983, January 1984, September 1984, and April 2007 to January 2010) are normalized to reference material Kil-93 (La/Sm of 2.09, average value from Australia National University where most ICP-MS analyses were performed). Vertical lines indicate nearly double magma supply rate between 2003 and 2007 [*Poland et al.*, 2012]. Trace-element abundances in ppm (data shown in supporting information). Average $\pm 2\sigma$ bars are shown in a corner of each panel. September 1982 Kīlauea summit lava composition from *Pietruszka and Garcia* [1999].

disequilibrium in the episode 54 lavas are thought to result from mixing Pu'u 'Ō'ō magma with stored, differentiated rift zone magma [*Garcia et al.*, 2000; *Thornber et al.*, 2003]. In contrast, episode 56 lavas have higher MgO (8.5 versus 7.2 wt %) and a relatively high $\delta^{18}O$ value (5.6 versus 5.4‰) but are otherwise geochemically indistinguishable from contemporaneous Pu'u 'Ō'ō lavas.

[12] The $^{206}Pb/^{204}Pb$ ratios for Pu'u 'Ō'ō lavas decreased rapidly through the episodic fountaining period (1983–1986) and reached a minimum between 1989 and 1991 during the Kupaianaha phase (Figure 4b and Table 2). The rapid decrease in $^{206}Pb/^{204}Pb$ continues the longer-term trend of decreasing Pb isotope ratios for Kīlauea lavas erupted following the 1924 collapse of the summit caldera (Figure 4a). After 1991, the trend of $^{206}Pb/^{204}Pb$ ratios in Pu'u 'Ō'ō lavas shows cyclic variations with two broad humps, each cycle spanning approximately 10 years (except for a small offset from the overall trend between January 1998 and June 1999; Figure 4b). The cyclic variation in Pb isotope ratios is well shown by $^{208}Pb/^{206}Pb$ ratios, which inversely mirror the $^{206}Pb/^{204}Pb$ trend (Figures 4 and 5).

[13] The $^{87}Sr/^{86}Sr$ ratios of Pu'u 'Ō'ō lavas extend the temporal trend of increasing Sr isotope ratios for Kīlauea lavas that started following the 1924 caldera collapse (Figure 4c). Overall, Pu'u 'Ō'ō lavas display an increase in $^{87}Sr/^{86}Sr$ from 1983 to ~2003 and a slight decrease after 2004 (Figure 4d). Prior to 1999, the $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ ratios of the lavas are not well correlated, although there is an overall inverse correlation between the

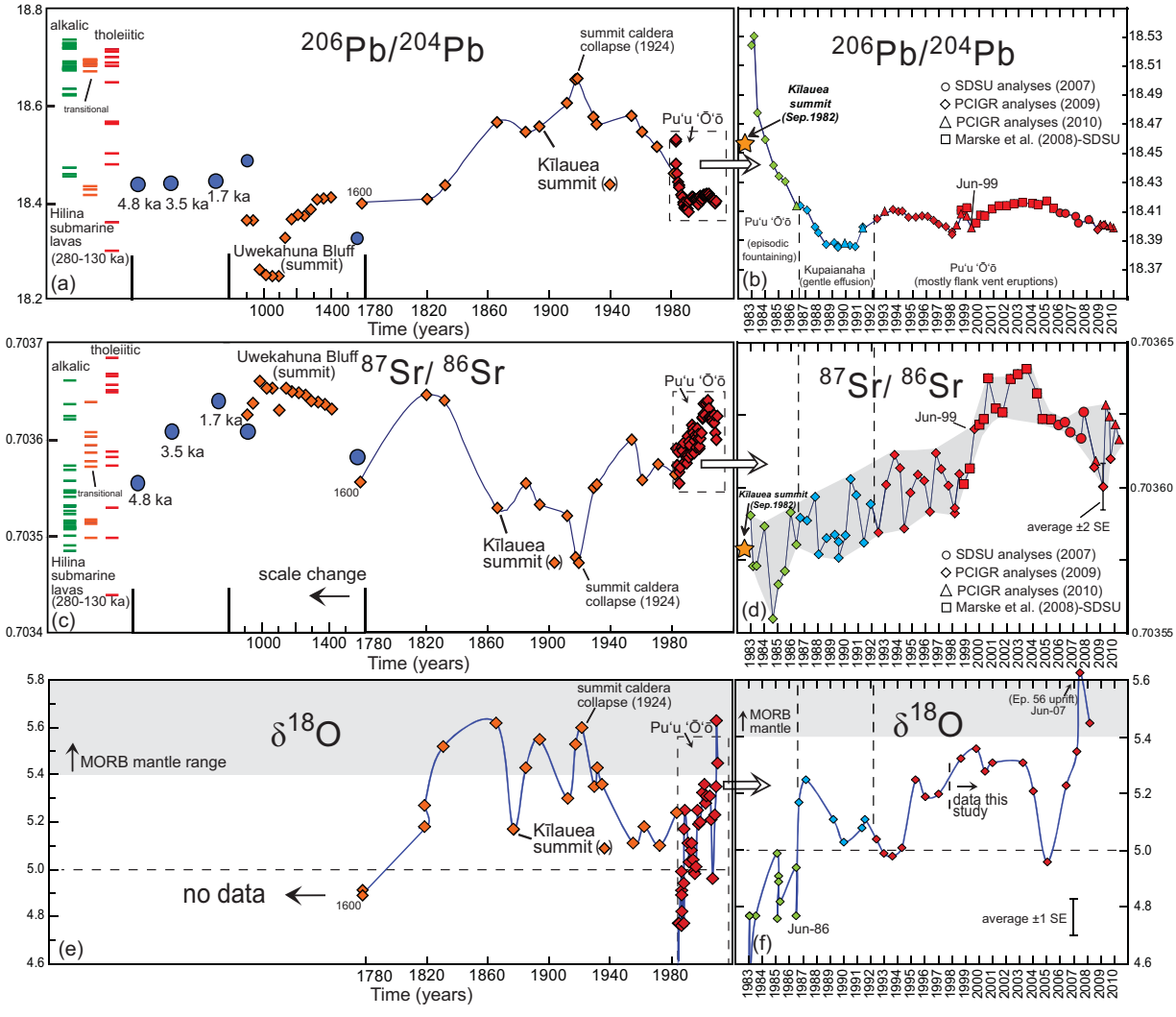

Figure 4. Temporal variation of Pb, Sr, and O isotopes for Kīlauea Volcano and Pu'u 'Ō'ō lavas. (b) $^{206}Pb/^{204}Pb$ in Pu'u 'Ō'ō lavas shows cyclic variation with two broad humps, each cycle spanning approximately 10 years. (d) $^{87}Sr/^{86}Sr$ in Pu'u 'Ō'ō lavas increases from 1983 to 2003 and decreases between 2008 and 2010, and is correlated with $^{206}Pb/^{204}Pb$ after 1999. (f) $\delta^{18}O$ for Pu'u 'Ō'ō lavas shows the same range (0.7‰) as historical Kīlauea summit lavas and is not well correlated with $^{206}Pb/^{204}Pb$ or $^{87}Sr/^{86}Sr$. Data sources for Kīlauea Volcano are *Hanyu et al.* [2010], *Kimura et al.* [2006], *Marske et al.* [2007], *Abouchami et al.* [2005], *Pietruszka and Garcia* [1999], *Chen et al.* [1996], and *Garcia et al.* [2008]. Data sources for previous analyses of Pu'u 'Ō'ō lavas are *Marske et al.* [2008] and *Garcia et al.* [1998]. For Pu'u 'Ō'ō analyses, average $\pm 2\sigma$ for $^{206}Pb/^{204}Pb$ is smaller than symbol size and uncertainty for $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ is shown in the panels. Data for Pu'u 'Ō'ō lavas are presented in Table 2. September 1982 Kīlauea summit lava composition from *Pietruszka and Garcia* [1999]. Colors for symbols in Figures 4b, 4d, and 4f) are the same as Figure 3.

two ratios for historical summit lavas (Figure 4 and Table 2). After 1999, there is a positive correlation between $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ (Figure 6), which corresponds to the second of the two major temporal cycles of Pb isotope ratios (Figure 5). The Nd isotope ratios of lavas erupted between 1983 and 2005 display no variation outside analytical uncertainty [*Marske et al.*, 2008]. Thus, no new Nd isotopic data were collected during this study.

[14] Oxygen isotopic compositions of Pu'u 'Ō'ō lavas erupted over 25 years (1983–2008) show a larger range than historical Kīlauea summit lavas spanning ~380 years of activity (1.1 versus 0.7‰; Figure 4). Overall, O isotope ratios of Pu'u 'Ō'ō lavas have increased over time with early lavas (before 1986) having lower $\delta^{18}O$ (4.8–4.9‰) than subsequent lavas (5.0–5.6‰; Table 2). The highest O isotope ratio observed during the Pu'u 'Ō'ō eruption is for an episode 56 lava that erupted ~6

km uprift from the Pu'u 'Ō'ō vent in mid-June 2007. The episode 56 eruption is related to intrusion of a dike from the upper East Rift Zone, so this lava was probably not derived from the shallow reservoir of magma beneath Pu'u 'Ō'ō [*Montgomery-Brown et al*., 2010]. Thus, its $\delta^{18}O$ value is probably representative of the magma feeding the Pu'u 'Ō'ō eruption. It is identical to the highest values observed among historical summit lavas (5.6‰; Figure 4). Variations of $\delta^{18}O$ in Pu'u 'Ō'ō lavas do not correlate with Pb or Sr isotope ratios, or with other geochemical parameters, as was noted for previous O isotope work on lavas from this eruption [*Garcia et al*., 1998]. Therefore, Pu'u 'Ō'ō lava Pb and Sr isotope ratios were apparently not affected by the processes causing variable O isotope ratios.

5. Discussion

[15] The high eruption rate and continuous nature of the Pu'u 'Ō'ō eruption provide an exceptional opportunity to use lava chemistry to evaluate the changing roles that source, melting, and crustal processes play during this single prolonged eruption. Previous Pb isotope and trace-element studies on lavas from several multiple-year eruptions of Piton de la Fournaise Volcano (Réunion Island) have discerned contributions from multiple components within the Réunion mantle plume and a periodic role for shallow-level contamination [*Pietruszka et al*., 2009; *Vlastélic et al*., 2005, 2007]. Similarly, extreme Pb isotope variability in melt inclusions from Iceland basaltic lavas indicate significant source heterogeneity, with binary mixing relationships that may result from combining solids in the mantle and two stages of melt mixing (in porous mantle melt-transport channels and lower crustal magma chambers) [*Maclennan*, 2008]. Similarly, the geochemistry and petrography of Pu'u 'Ō'ō lavas have been used to interpret the extent of crustal magmatic processes (olivine fractionation and accumulation, mixing of higher-MgO and stored rift-zone magmas, and crustal assimilation) and mantle processes (degree of partial melting, melt extraction and migration, and source heterogeneity) during the Pu'u 'Ō'ō eruption until 2005 [e.g., *Garcia et al*., 1998, 2000; *Marske et al*., 2008]. Here we use new high-precision Pb, Sr, and O isotope ratios, and major- and trace-element data for the entire Pu'u 'Ō'ō eruption (1983–2010) to evaluate the causes of cyclic and other short-term variability in the processes that operate from the source to the surface within Kīlauea Volcano. The effects of crustal processes (crystal fractionation, magma mixing, and crustal contamination) on modifying Pu'u 'Ō'ō lava compositions are evaluated before examining mantle source and melt transport processes.

5.1. Magma Mixing and Crystal Fractionation During Early Episodic Activity (1983–1985)

[16] The largest compositional changes in Pu'u 'Ō'ō lavas occurred from 1983 to 1985. These changes mostly involved two crustal processes: crystal fractionation and magma mixing. During some single eruptive episodes (5–10, 30, and 31), there were relatively large changes in MgO, Ni, and Cr, which are related to minor (3–5%) olivine fractionation in the shallow Pu'u 'Ō'ō reservoir during eruptive hiatuses [*Garcia et al*., 1992]. These short-term (3–4 weeks) variations are superimposed on longer term changes that have been related to magma mixing [*Garcia et al*., 1992; *Thornber*, 2003]. The longer term variations are evident in plots of MgO-normalized major elements, ratios of incompatible trace elements, and Pb isotope ratios (Figures 2–4). Strontium and O isotopes show less change during this period compared to their overall variation during the eruption (Figure 4). The overall progressive compositional variation in Pu'u 'Ō'ō lavas from 1983–1985 has been attributed to the mixing of new, relatively MgO-rich magma (>7.5 wt %) with a decreasing proportion of hybrid, rift-zone stored differentiated magma (from ~30% of the higher MgO magma in March 1983 to ~100% in September 1984) [*Garcia et al*., 1992; *Shamberger and Garcia*, 2007].

[17] The origin of the higher MgO magma component from the early phase of the Pu'u 'Ō'ō eruption may have been: (1) magma from the summit reservoir, as represented by lavas from the September 1982 summit eruption; and/or (2) new mantle-derived magma [*Garcia et al*., 1992; *Shamberger and Garcia*, 2007]. Scenario 1 involves no change in the composition of the higher MgO magma from September 1982 to 1985, whereas scenario 2 requires it. The 1983–1985 Pu'u 'Ō'ō lavas have both higher and lower $^{206}Pb/^{204}Pb$ ratios than the September 1982 summit lavas (Figures 4b and 7). Therefore, mixing of a single 1982 summit magma with rift-zone stored magma (scenario 1) cannot explain the isotopic

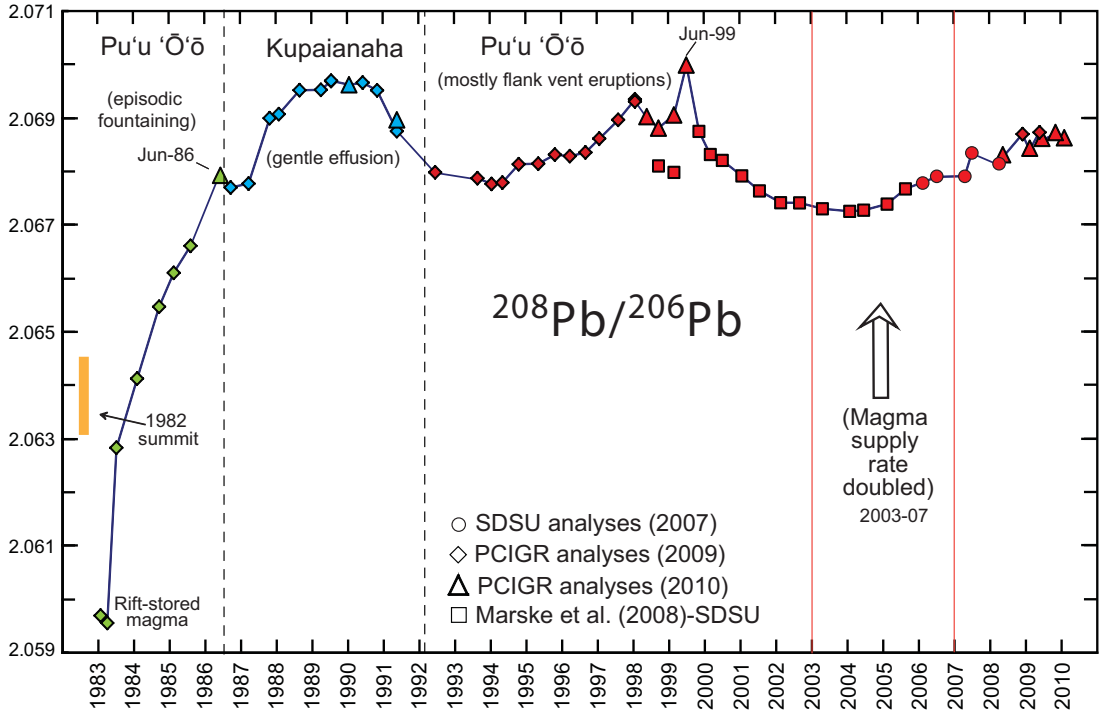

Figure 5. $^{208}Pb/^{206}Pb$ variation with time for Pu'u 'Ō'ō lavas from 1983 to 2010. Previous analyses of Pu'u 'Ō'ō lavas indicated in legend are from *Marske et al*. [2008]. Average $\pm 2\sigma$ for $^{208}Pb/^{206}Pb$ is smaller than symbol size.

variation of Pu'u 'Ō'ō lavas after ~1984, when $^{206}Pb/^{204}Pb$ values are lower than 1982 summit magma (Figure 7). Ratios of some incompatible trace elements (Sr/Nb and Zr/Nb) for some lavas with higher MgO (>7.5 wt %) erupted after mid-1984 also are higher than those for September 1982 summit lavas (Figure 3). Thus, if magma from the summit reservoir was supplying the Pu'u 'Ō'ō eruption, its composition must have changed after the September 1982 eruption and prior to September 1984 (Figures 4 and 7).

[18] The isotopic variations for early Pu'u 'Ō'ō lavas are consistent with the eruption being supplied by new, compositionally variable, mantle-derived magma in addition to or instead of September 1982 summit magma. The rate of $^{206}Pb/^{204}Pb$ variation observed for the period after the end of early magma mixing is much faster than during the previous 30 years (1952–1982) of Kīlauea summit eruptions (0.016 yr^{-1} versus 0.004 yr^{-1}). These rapid variations in Pb isotopic ratios suggest that magmas supplying Pu'u 'Ō'ō partially bypassed or did not thoroughly mix with the summit reservoir [*Garcia et al*., 1996]. Based on these observations, the composition of the parental magma delivered to Pu'u 'Ō'ō from the mantle is interpreted to have continually changed for the remainder of the eruption (i.e., after 1984). The details and cause of this variation are discussed in section 5.3.

5.2. Oxygen Isotope Indications of Crustal Contamination and Nature of Mantle Source

[19] Lavas from oceanic island volcanoes show wide ranges in oxygen isotopic compositions (4.5–7.5‰), which have been attributed to compositionally variable mantle-derived magmas that were modified by oxygen exchange and/or crustal contamination [*Harmon and Hoefs*, 1995]. Our previous studies revealed that some Pu'u 'Ō'ō and Kīlauea summit magmas experienced significant oxygen isotope exchange with metamorphosed Kīlauea rocks [*Garcia et al*., 1998, 2008]. This is indicated by the disequilibrium between matrix and coexisting olivine $\delta^{18}O$ values, the relatively low $\delta^{18}O$ values for these lavas (4.7–5.2‰) and the lack of correlation between $\delta^{18}O$ values and other geochemical parameters [*Garcia et al*., 1998, 2008].

[20] The highest $\delta^{18}O$ value observed for any lava during the Pu'u 'Ō'ō eruption is for the June 2007

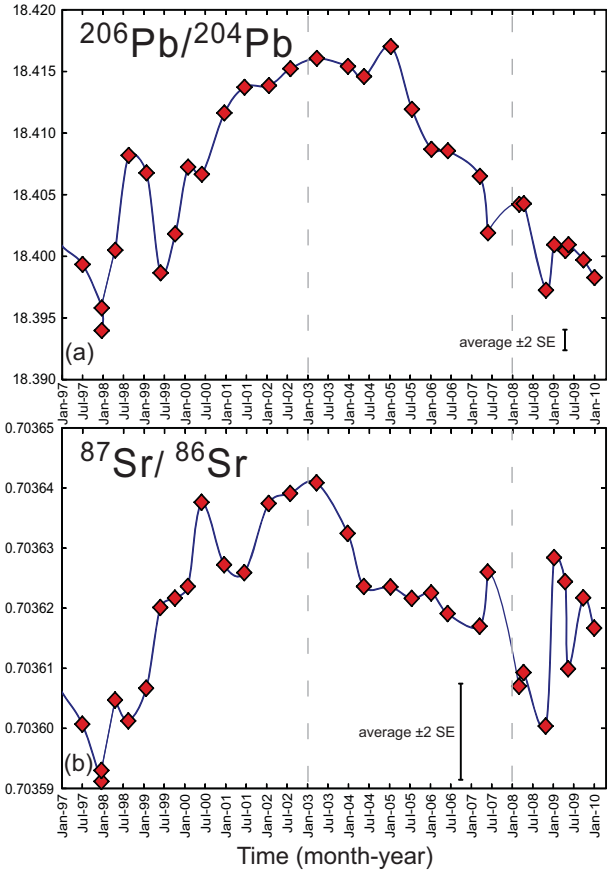

Figure 6. Temporal variation in $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ for Pu'u 'Ō'ō lavas during period of dramatic increase in magma supply. Dashed lines indicates period of significant increase in magma supply rate up to 0.25 km^3/yr between ~2003 and 2007 compared to ~0.1 km^3/yr prior to 2003 [*Poland et al*., 2012]. Analytical uncertainty is shown in the panels.

uprift lava (5.6‰; Figure 4). This value is identical to the highest value reported for historical Kīlauea summit lavas (1820–1982) [*Garcia et al*., 2008] and lies within the range of normal mid-ocean ridge basalt (MORB) basalt $\delta^{18}O$ values (5.4–5.8‰; Figure 4) [*Eiler*, 2001]. These summit lavas (1832, 1866, 1894, and 1917–1921) were erupted during periods of sustained lava lake activity, and are thought to be representative of the primary uncontaminated magma feeding Kīlauea [*Garcia et al*., 2008]. Thus, the 2007 uprift vent lava supports our previous interpretation [*Garcia et al*., 2008] that the $\delta^{18}O$ value for the mantle source of Kīlauea's magma is identical to the source for MORB.

[21] The earliest Pu'u 'Ō'ō lavas (1983–1986) show the strongest signs of disequilibrium between coexisting matrix mineral and olivine, and have the lowest O isotope values (<5.0‰) [*Garcia et al*., 1998]. After the shift to continuous effusion in July 1986, O isotope ratios are higher (5.2‰) and the coexisting olivines were in equilibrium with host matrix for about 1 year [*Garcia et al*., 1998]. Subsequently, the matrix O isotope values decreased somewhat (to ~5.0‰; Figure 4) and those for olivine increased, indicating olivine-matrix disequilibrium. This O isotope disequilibrium continued for two more years, and was followed by a return to olivine-matrix equilibrium in 1995–1997 [*Garcia et al*., 1998]. After 1997, matrix O isotope values are relatively low and nearly constant (5.3 ± 0.1‰) except for a 2005 lava (5.0‰; Figure 4), which was the most evolved sample (analyzed for O isotopes) since 1984 (6.7 wt % MgO). Thus, despite nearly 30 years of vigorous eruptive activity (producing ~4 km^3 of lava), oxygen exchange with metamorphosed rocks has probably continued in the Pu'u 'Ō'ō magmatic plumbing system. The magnitude of oxygen isotope exchange can be estimated assuming bulk assimilation between a parental magma (as reflected by the 2007 uprift sample with a $\delta^{18}O$ value of 5.6‰) and a hydrothermally altered Kīlauea rift zone lava (1.9‰) [*Garcia et al*., 2008] as a contaminant. Pu'u 'Ō'ō lavas erupted just before and after the 2007 uprift event have average O isotope values of 5.4‰ (Figure 4), indicating ~5% bulk contamination, whereas earlier lavas (1986–2006) with average values of 5.2–5.3‰, might have experienced 8–11% bulk contamination. This contamination is likely to have occurred in the Pu'u 'Ō'ō reservoir and did not have any obvious effect on other geochemical parameters [*Garcia et al*., 1998] (Table 2).

5.3. Cyclic Compositional Variations From Mantle Processes (1985–2010)

[22] Pu'u 'Ō'ō lavas erupted after the early period of magma mixing ended in late 1984 show cyclic variations in several geochemical parameters that are insensitive to olivine fractionation (e.g., CaO/TiO_2, Sr/Nb, Zr/Nb, $^{206}Pb/^{204}Pb$; Figure 8). The cyclic variations in CaO/TiO_2 and K_2O/TiO_2 ratios for Pu'u 'Ō'ō lavas erupted between 1996 and 2001 were reported to be associated with deformation in the summit magma reservoir [*Thornber*, 2003]. Although the timing of the highs and lows in these ratios are not perfectly coincident with summit tilt changes [see Figure 8, *Thornber*, 2003], these geochemical cycles were attributed to mixing of mantle-derived magma of uniform composition (similar to Pu'u 'Ō'ō lavas

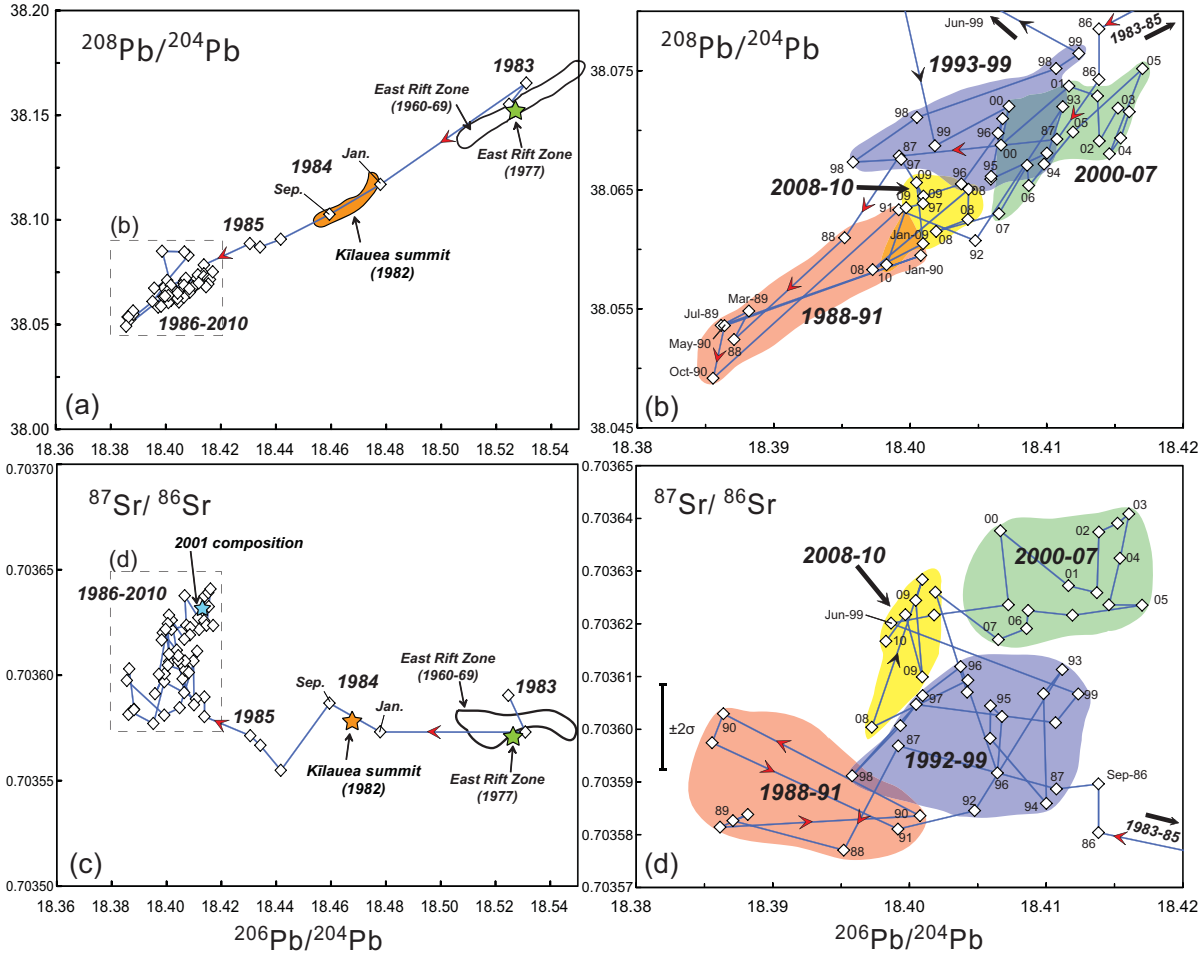

Figure 7. Pb and Sr isotopic compositions for Pu'u 'Ō'ō lavas. Line connects samples in order of increasing eruption date in Figures 7b and 7d. Average $\pm 2\sigma$ for Pb isotope ratios is smaller than symbol size. East Rift Zone data is from J. Marske [personal communication, 2013]. September 1982 Kīlauea summit lava composition (outline in Figure 7a; orange star in Figure 7c) from *Pietruszka and Garcia* [1999]. Kīlauea summit (1982) field in Figure 7a is new high-precision data from A. Pietruszka [personal communication, 2013]. Blue star is 2001 composition proposed by *Thornber* [2003] as mixing end-member with 1982 Kīlauea summit composition. Pu'u 'Ō'ō lavas erupted after ~1999 have elevated $^{87}Sr/^{86}Sr$ ratios (at a given $^{206}Pb/^{204}Pb$). The 1999–2001 lavas cannot serve as mixing end-members to explain the compositional trend of lavas erupted before ~1999.

from 1999 to 2001) with 1982 summit magma [*Thornber* 2003]. However, Pu'u 'Ō'ō lavas erupted after ~1999 have elevated $^{87}Sr/^{86}Sr$ ratios (at a given $^{206}Pb/^{204}Pb$; Figure 7) compared to earlier lavas with low $^{206}Pb/^{204}Pb$ ratios, and thus, the 1999–2001 lavas cannot serve as a mixing end-members to explain the compositional trend of lavas erupted before 1999. Similar behavior is observed on a plot of La/Yb versus $^{206}Pb/^{204}Pb$ (Figure 9), where a relative shift to lower La/Yb ratios at a given $^{206}Pb/^{204}Pb$ occurred after ~1999 (compared to the trend of pre-1999 lavas). These relationships indicate that the temporal variation of Pu'u 'Ō'ō lavas erupted after 1999 cannot be explained simply by mixing of 1982 summit magma with a uniform mantle-derived magma (Figure 7) within Kīlauea's shallow magmatic plumbing system. Instead, either a third magma is mixing with the other two or, as we advocate below, the composition of the Pu'u 'Ō'ō magma is continually changing due to the melting of small-scale compositional heterogeneities in the mantle source.

[23] Ratios of Pb isotopes in Pu'u 'Ō'ō lavas show cyclic variations (Figure 5). These variations probably reflect the dynamic process of melt extraction (from a heterogeneous source) over a time scale of

years to decades rather than movement of small-scale mantle heterogeneities through the melting zone. This interpretation is based on the hypothesis that buoyancy-driven upwelling through the melt-producing region beneath Kīlauea occurs on longer timescales (hundreds to thousands of years) than melt extraction (years to decades) [*Pietruszka et al*., 2006]. The highest estimates for solid mantle upwelling in the center of the Hawaiian plume are ~10 m/yr [*Hauri*, 1996; *Pietruszka and Garcia*, 1999], which would result in a maximum of only ~270 m of upwelling during the first 27 years of the Pu'u 'Ō'ō eruption [cf. ~5–10 km maximum thickness for the zone of melting; *Marske et al*., 2007]. For comparison, estimates for solid mantle upwelling rates beneath Mauna Loa and Lō'ihi based on U-series disequilibria range from ~0.4 to 1 m/yr [*Sims et al*., 1999] and ~5–6 cm/yr [*Pietruszka et al*., 2011], respectively. Melt extraction rates (or source-to-surface melt velocity) are estimated to be on the order of 5–17 km/yr [*Reiners*, 2002], which is extremely rapid compared to solid mantle upwelling rates. Thus, cyclic variation in Pb isotope ratios over short timescales (years) are best explained by variations in the process of melting of a heterogeneous source (and the transport of the melt to the surface), rather than upwelling of small-scale mantle heterogeneities through the melting region.

[24] The short-term Pb and Sr isotopic variations in Pu'u 'Ō'ō lavas may be generated by one or more processes including: periodic processes of melting, melt extraction, or melt aggregation [e.g., *Cordier et al*., 2010], changes in melt transport pathways or tapping new source areas [*Marske et al*., 2008; *Pietruszka et al*., 2006], changes in the volume of the melting region [*Pietruszka et al*., 2001], and progressive melt extraction from a source with fine-scale heterogeneities [*Garcia et al*., 2000]. In the presence of small-scale heterogeneities, changes in melt pathways over years to decades may lead to tapping compositionally distinct sources and short-term isotopic variation in lavas [*Marske et al*., 2007]. The scale of compositional heterogeneities must be small relative to the size of the melting region beneath Kīlauea Volcano to allow for rapid (few years) variation in lava Pb isotope compositions [*Pietruszka and Garcia*, 1999]. Melt pathways within the source region probably migrate over years to decades [*Pietruszka et al*., 2001, 2006]. Therefore, melt may be supplied from different areas of the melting region

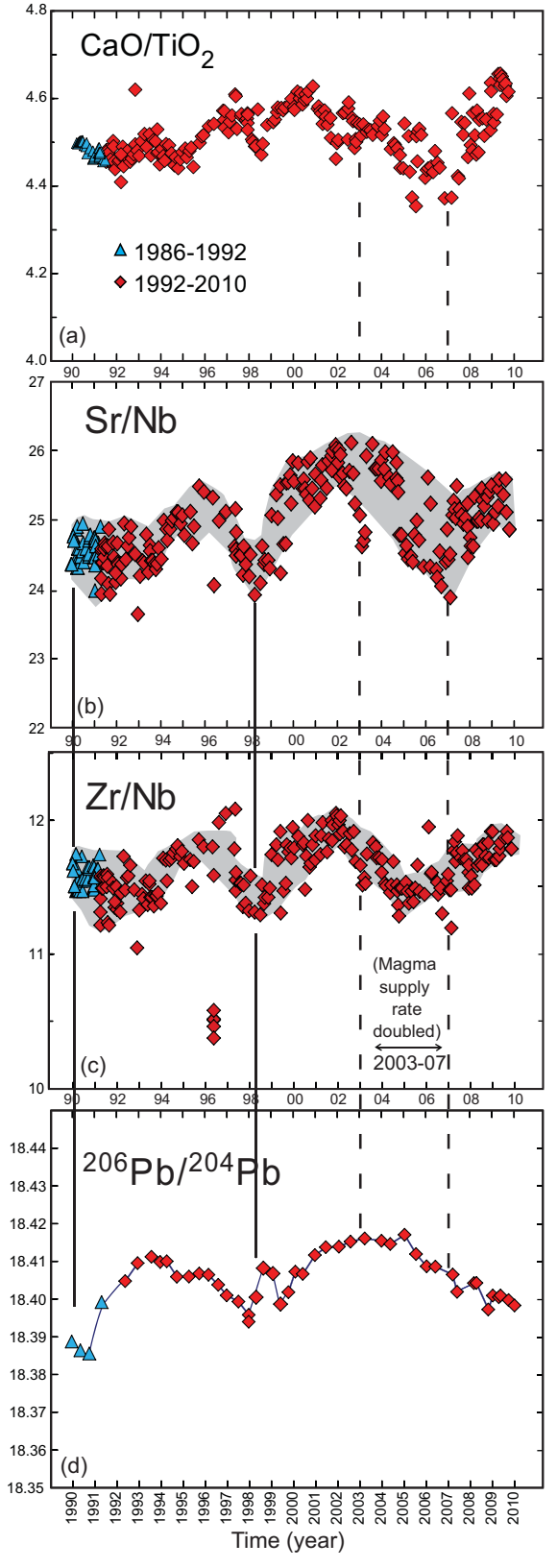

Figure 8. Plots of CaO/TiO_2, Sr/Nb, Zr/Nb and $^{206}Pb/^{204}Pb$ for Pu'u 'Ō'ō lavas showing cyclic variation apparent from 1990 to 2010. Trace-element abundances in ppm.

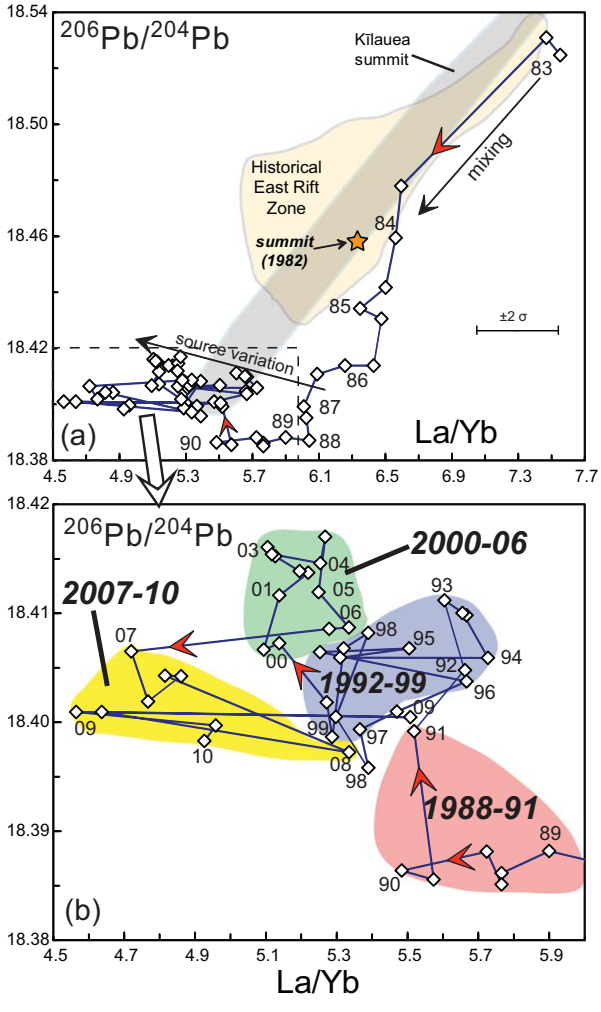

Figure 9. Plots of $^{206}Pb/^{204}Pb$ versus La/Yb for Pu'u 'Ō'ō lavas with line connecting samples in eruptive order. (a) All Pu'u 'Ō'ō lavas. (b) Smaller variations in lavas erupted between 1988 and 2010 [area indicated by box with dashed line in Figure 9a]. Kīlauea summit data is from *Pietruszka and Garcia* [1999]. Average $\pm 2\sigma$ for La/Yb shown in Figure 9 a. Average $\pm 2\sigma$ for Pb isotope ratios is smaller than symbol size.

over a relatively short period of time. These short-term geochemical fluctuations are effectively transported from the source to the surface because Pu'u 'Ō'ō magmas are thought to partially bypass the volcano's summit magma storage reservoir, and avoid its buffering effects [*Garcia et al.*, 2000].

[25] The periodicity and rate of isotopic variation Pu'u 'Ō'ō lavas provide clues about the size and distribution of small-scale heterogeneities in the volcano's mantle source. The cycles of Pb isotopic ratios at Pu'u 'Ō'ō have a peak to peak duration of ~10 years (Figure 10). These short-term increases and decreases of Pb isotope ratios, at similar rate and degree, may represent melt extraction from small-scale heterogeneities with a limited horizontal length scale (a few km or less). Modeling by *Farnetani and Hofmann* [2009] suggests that "filament-like" structures derived from stretching of deep-seated mantle heterogeneities may develop as the Hawaiian plume rises to the surface. Although their model was developed to explain the long-term (>100 kyr) geochemical variation observed for drill core from Mauna Kea [*Farnetani and Hofmann*, 2010], we use the filament model to explain the periodic variation in the Pb isotope ratios of Pu'u 'Ō'ō lavas (Figure 10) because it provides a mechanism to link geochemical variations with the inferred deep mantle structure. Other geometries have been suggested for the small-scale heterogeneities within Hawaiian plume, including a series of vertically stacked, elongated blobs [*Blichert-Toft and Albarède*, 2009], but we prefer the filament geometry to explain the Pb isotopic variations of Pu'u 'Ō'ō lavas.

[26] In this scenario, the periodic variation in Pb isotope ratios of Pu'u 'Ō'ō lavas may reflect melt extraction from a mantle source with vertically oriented repeating source heterogeneities, or thin strands, on a small scale (Figure 10). The Pu'u 'Ō'ō eruption rate is thought to be greater than the rate of melting, so melt must be transferred into chemically isolated channels from successively further areas within the larger melting region to sustain the eruption [*Pietruszka et al.*, 2006]. In the context of the filament model of *Farnetani and Hofmann* [2009], this process might extract melt from a succession of strands with different isotopic compositions, which would potentially create the observed periodicity in variation of the Pb isotope ratios (Figure 10). The volume of a single compositional strand within the mantle tapped by the Pu'u 'Ō'ō eruption can be inferred using estimates for lava eruption rate (~0.13 km^3/yr) [*Sutton et al.*, 2003] and melt zone porosity (1–2%) [*Pietruszka et al.*, 2001]. This calculation assumes that (1) there have been only two isotopically distinct components since ~1986 and (2) the heterogeneities have the same melt productivity. We do not consider the effect of melting heterogeneous lithologies with different melt productivities (e.g., peridotite versus pyroxenite), despite the potential significance for mixed lithologies in the source for Hawaiian lavas [*Hauri*, 1996; *Reiners*, 2002; *Sobolev et al.*, 2005]. Indeed, recent modeling of incompatible trace elements suggests that Pu'u

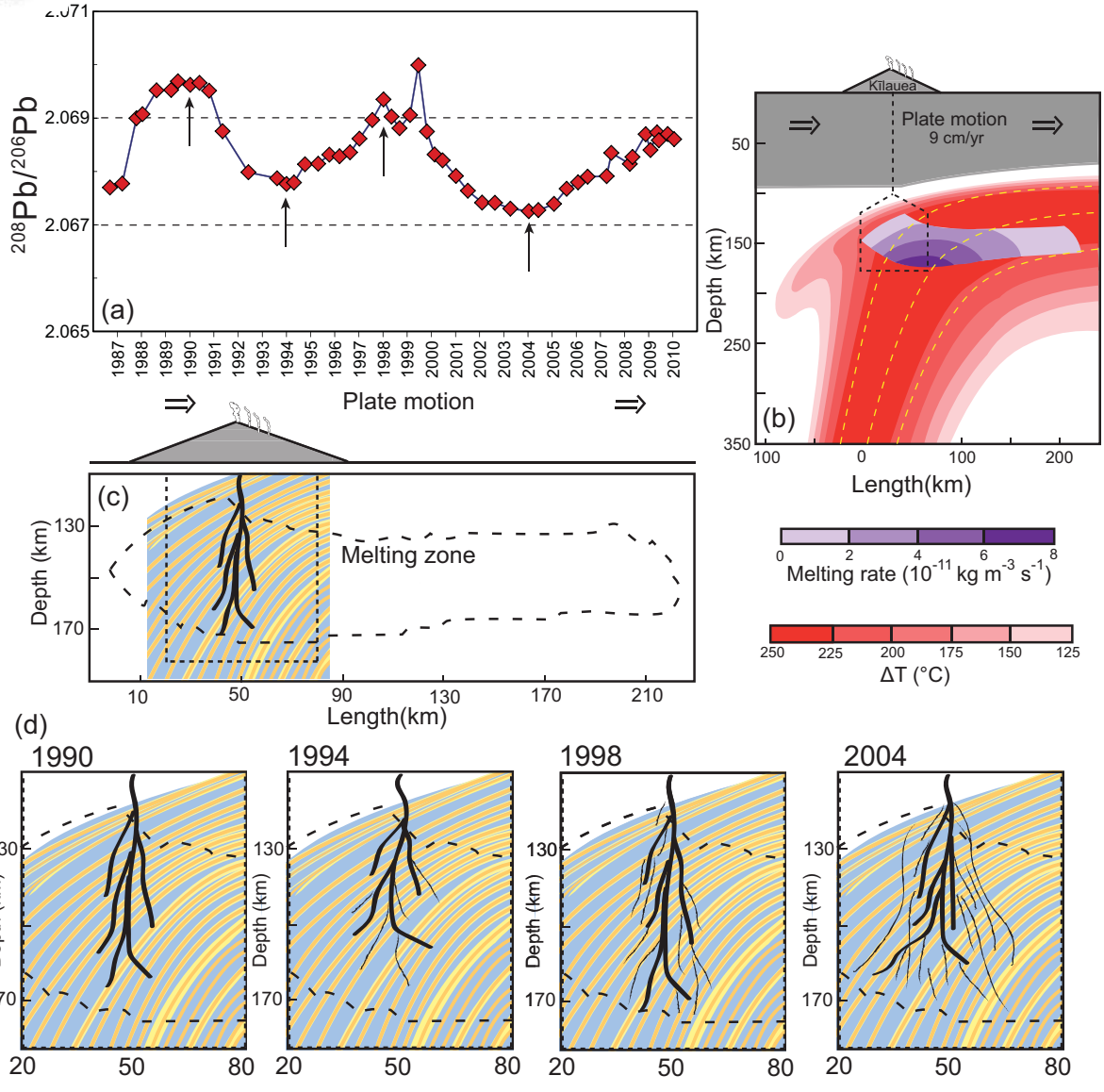

Figure 10. Cartoon model for the Hawaiian mantle plume to explain the isotopic variation of Pu'u 'Ō'ō lavas, based on assumptions described in the text. (a) $^{208}Pb/^{206}Pb$ variation with time for Pu'u 'Ō'ō lavas from 1990 to 2010 showing cyclic variation. (b) Vertical section of the Hawaiian plume adapted from *Farnetani and Hofmann* [2010]. Purple shades indicate the melting rates inside the melting zone, shown in legend. Dashed yellow lines are flow trajectories. Dashed black box is magma capture zone for Kīlauea. (c and d) Sketches of the changing melting zone during Pu'u 'Ō'ō eruption. Lithosphere is not shown in Figure 10c. Melting zone from *Farnetani and Hofmann* [2010].

'Ō'ō lavas (1986–1998) are derived from a source with ~13% recycled oceanic crust in a matrix of ambient depleted Hawaiian mantle [*Pietruszka et al.*, 2013]. However, this model was unable to distinguish if the recycled oceanic crust was present as pyroxenite or refertilized peridotite. It should also be noted that the compositional range of Pu'u 'Ō'ō lavas from 1986 to 2010 is small compared to the overall range for Hawaiian volcanoes [e.g., *Jackson et al.*, 2012; *Ren et al.*, 2009; *Weis et al.*, 2011], so the melt productivities of the end-member sources are probably similar.

[27] The duration of a single cycle of Pb isotope variation is approximately 10 years (Figure 10), which suggests melt is extracted from one compositional strand in ~5 years (before the trend reverses when melt from a different strand is encountered). Estimates for the height of Kīlauea's melting region range from <5 km [*Marske et al.*, 2008] to 55 km [*Watson and McKenzie*, 1991]. We assume the magma supply rate is roughly equivalent to the eruption rate given that overall magma storage in Kīlauea has been decreasing slightly since 1983 [*Poland et al.*, 2012]. The melt

volume produced in 5 years is ~0.5 km^3. If melt zone porosity is ~2% (estimates based on U-series studies range from 1 to 3%) [*Pietruszka et al.*, 2001; *Sims et al.*, 1999], the total volume of a single heterogeneity tapped over a 5 year period would be ~25 km^3. If individual filament-shaped heterogeneities extend over the height of the melting zone, then this 25 km^3 volume would translate to a diameter of ~1–3 km for melting zone heights of 55–5 km, respectively.

5.4. Effects of Doubling of Magma Supply Rate on Lava Composition (2003–2007)

[28] One enigmatic question of ocean island volcanism is whether variations in lava compositions are correlated with magma supply rate [e.g., *Vlastélic et al.*, 2005]. Wide variations in magma supply rate have occurred historically at Kīlauea (0.01–0.18 km^3/yr between 1840 and 1983) [*Dvorak and Dzurisin*, 1993]. A marked decrease in lava effusion rate during the 19th to early 20th century at Kīlauea (0.10–0.01 km^3/yr) was accompanied by an increase in the ratios of highly over moderately incompatible trace-element abundances [*Pietruszka and Garcia*, 1999], and in the modal abundance of clinopyroxene and plagioclase in the lavas indicating eruption of more fractionated and cooler magma [*Garcia et al.*, 2003]. This change in lava composition is believed to be a direct result of a decrease in the melt fraction (10–5%) and a switch to a more depleted source [*Pietruszka and Garcia*, 1999]. A dramatic short-term increase in effusion rate was observed for the Pu'u 'Ō'ō eruption between 2003 and 2007 [*Poland et al.*, 2012]. Here we explore the results of this magma supply surge on the composition of Pu'u 'Ō'ō lavas.

[29] Estimates of lava effusion rate for the Pu'u 'Ō'ō eruption prior to 2003 are based on geologic mapping, and measurements of very low frequency electromagnetic profiling and gas emissions. These techniques indicate an average rate of magma supply of ~0.13 km^3/yr [*Sutton et al.*, 2003]. Lava effusion rate (considered to be a proxy for the magma supply rate by *Poland et al.* [2012]) was estimated to have increased between 2003 and 2007 and to have doubled in 2005 (to ~0.25 km^3/yr), before returning to the previous rate by 2008 [*Poland et al.*, 2012]. An increase in magma supply is normally expected to result in higher MgO contents in erupted lavas as magma undergoes less cooling prior to eruption. This relationship was inferred for Pu'u 'Ō'ō lavas erupted from 1986 to 1992, when changes in tilt were followed ~3 weeks later by changes in MgO [e.g., *Garcia et al.*, 1996]. However, during the 2003–2007 surge in magma supply, Pu'u 'Ō'ō lavas have consistently lower MgO contents (<7.5 wt %; Figure 2a) than any period since the start of continuous effusion in mid-1986, except during episode 54. The lower MgO contents of 2003–2007 lavas was interpreted to have resulted from the stirring and flushing of cooler magma within the volcano's shallow magma storage system by an influx of new, hotter more primitive magma [*Poland et al.*, 2012]. Mineralogical evidence (two populations of olivine) was noted in support of this claim, although no data were presented by *Poland et al.* [2012]. Our previous study of olivine compositions in lavas erupted before and during the surge found no evidence for two populations of olivines in any of the lavas, and that olivines in these weakly phyric rocks are in Fe-Mg equilibrium with the whole rock [*Marske et al.*, 2008]. We re-examined thin sections for these lavas and found no textural evidence indicating magma mixing. In contrast, Pu'u 'Ō'ō lavas from 1983 to 1984 and episode 54 display obvious disequilibrium features from magma mixing [*Garcia et al.*, 1989, 2000]. If mixing with a stored, cooler magma was important during the 2003–2007 surge in magma supply, the stored component must not have differentiated very far beyond olivine control (unlike the situation for Pu'u 'Ō'ō lavas from 1983 to 1984 and episode 54).

[30] A small increase in lava MgO content occurred after the surge, although values were variable and overlap with those during the surge (7.0–8.1 after versus 6.7–7.4 wt % MgO during; Figure 2). The higher post-surge MgO values were interpreted to be a result of the heightened magma supply from 2003 to 2007 [*Poland et al.*, 2012]. By November 2008, MgO dropped to values similar to and lower than during the surge (6.5–7.2 wt %; Figure 2). Since 2000, the MgO content of Pu'u 'Ō'ō lava has been declining with no significant change of this overall trend during the 2003–2007 surge in magma supply (Figure 2), except for less scatter in MgO content which may simply reflect fewer interruptions in effusion during this time. Also, it is noteworthy that the highest sustained MgO values were observed for Pu'u 'Ō'ō lavas from 1988 to 1993 (Figure 2), a period when no increase in magma supply was recorded [*Poland et al.*, 2012; *Sutton et al.*, 2003]. Thus, the increase in magma supply from 2003 to 2007 appears to have had limited impact on the variation in the MgO content of Pu'u 'Ō'ō lavas.

[31] Some of the other compositional features of the lavas erupted during the 2003–2007 magma surge (e.g., slight offsets to lower MgO-normalized SiO_2 contents, Zr/Nb ratios and higher normalized K_2O and TiO_2) could be considered to be representative of flushing of differentiated magma similar to the Pu'u 'Ō'ō lavas the late 1990s to early 2000s (Figures 2 and 3). There is also a reversal in $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ in 2004 toward values by ~2007 similar to lavas from ~2000 (Figure 6). These trends might be explained by the flushing of magma stored since the late 1990s to early 2000s during the 2003–2007 surge in magma supply. However, based on the close time correlations (weeks to few months) between changes in summit tilt and lava composition in earlier Pu'u 'Ō'ō lavas [*Garcia et al*., 1996; *Thornber*, 2003], it is hard to imagine why 4+ years were required to flush cooler magma from the Pu'u 'Ō'ō system as proposed by *Poland et al*. [2012]. Thus, it is our interpretation that the magma erupted during the 2003–2007 surge was new mantle-derived magma and not stored magma flushed from Kīlauea's shallow crustal plumbing system. Thus, we interpret the isotopic variations during the Pu'u 'Ō'ō eruption (since ~1984) to be generated by the changing composition of melts coming from the mantle.

5.5. Comparison of Pu'u 'Ō'ō Lavas With the Long-Term Isotopic Evolution of Other Hawaiian Volcanoes

[32] Studies of the long-term geochemical variation of lavas from individual volcanoes in the Hawaiian Islands provide understanding of the chemical structure of the Hawaiian mantle plume [e.g., Loa and Kea trends, *Abouchami et al*., 2005; *Ren et al*., 2009; *Weis et al*., 2011], and the variability within single shield volcanoes [e.g., *Bryce et al*., 2005; *Chen and Frey*, 1985; *Eisele et al*., 2003; *Marske et al*., 2007; *Nobre Silva et al*., 2013; *Rhodes and Hart*, 1995; *Weis et al*., 2011]. Here we compare the short-term Pb and Sr isotopic variation for Pu'u 'Ō'ō lavas to the longer term variations for lavas from Kīlauea and nearby, well-studied shield volcanoes to better understand the rate and cause of long-term fluctuations observed at Hawaiian volcanoes.

[33] The Pu'u 'Ō'ō isotopic range covers a relatively large part of the long-term variation observed for Mauna Kea and Kīlauea volcanoes (Figures 11 and 12). The isotopic variation of nearby Mauna Kea volcano was well documented for ~300 kyr of shield growth using the HSDP2 drill core. Lavas from the Pu'u 'Ō'ō eruption after the period of magma mixing (early 1985) span ~30% of the total range of $^{206}Pb/^{204}Pb$ variation recorded for HSDP2 (0.07 versus 0.22). Compared to Kīlauea summit lavas, Pu'u 'Ō'ō lavas erupted since 1985 span ~25% of the Pb isotope range since 950 AD and ~47% of the range of Sr isotope ratios (Figures 4 and 12). Thus, this single eruption, which represents <1% of the time covered by the HSDP2 core and ~3% of the thousand-year period for Kīlauea summit lavas, shows remarkable short-term isotopic variations. However, as seen for Kīlauea summit lavas, isotopic variation in Hawaiian shield lavas is cyclic, with each volcano showing a narrow but commonly distinctive range (compared to neighboring volcanoes) as seen by the relatively tight fields for Pb and Sr isotope ratios in lavas from Kīlauea, Lō'ihi, Mauna Kea and Mauna Loa (Figure 12). Thus, the Pu'u 'Ō'ō eruption may represent the best known expression of the small-scale compositional heterogeneity of the Hawaiian plume. As discussed above, the rapid rates of isotopic fluctuation found in Pu'u 'Ō'ō lavas require a heterogeneous source (on a scale of less than several kilometers) that is tapped in only ~5 years of melt extraction. How does the Pu'u 'Ō'ō source compare with those for nearby, well studied volcanoes Lō'ihi and Mauna Kea?

[34] Compared to other Hawaiian volcanoes, the Sr and $^{206}Pb/^{204}Pb$ isotope ratios for Pu'u 'Ō'ō lavas are most similar to Lō'ihi (Figure 12), although Lō'ihi lavas have higher $^{208}Pb/^{204}Pb$ at a given $^{206}Pb/^{204}Pb$, like other Loa trend volcanoes (Figure 11). Pu'u 'Ō'ō lavas overlap with the Kea-mid8 Pb isotope array, the most common lava type in HSDP2 drill core (Figures 11c and 11d) [*Eisele et al*., 2003; *Nobre Silva et al*., 2013]. However, Sr isotopic compositions of Pu'u 'Ō'ō lavas erupted since ~1988 do not overlap those of Mauna Kea and trend orthogonally to the overall inverse array for Hawaiian shield volcanoes and for Kīlauea summit lavas (Figure 12). Thus, the Pu'u 'Ō'ō source is isotopically distinct from other Hawaiian volcanoes and the Pu'u 'Ō'ō data set shows that individual eruptions may have trends orthogonal to what are considered the primary source endmembers for Hawaiian shield volcanoes.

6. Conclusions

[35] The temporal geochemical variation of Pu'u 'Ō'ō lavas from 1983 to 2010 provides insights on

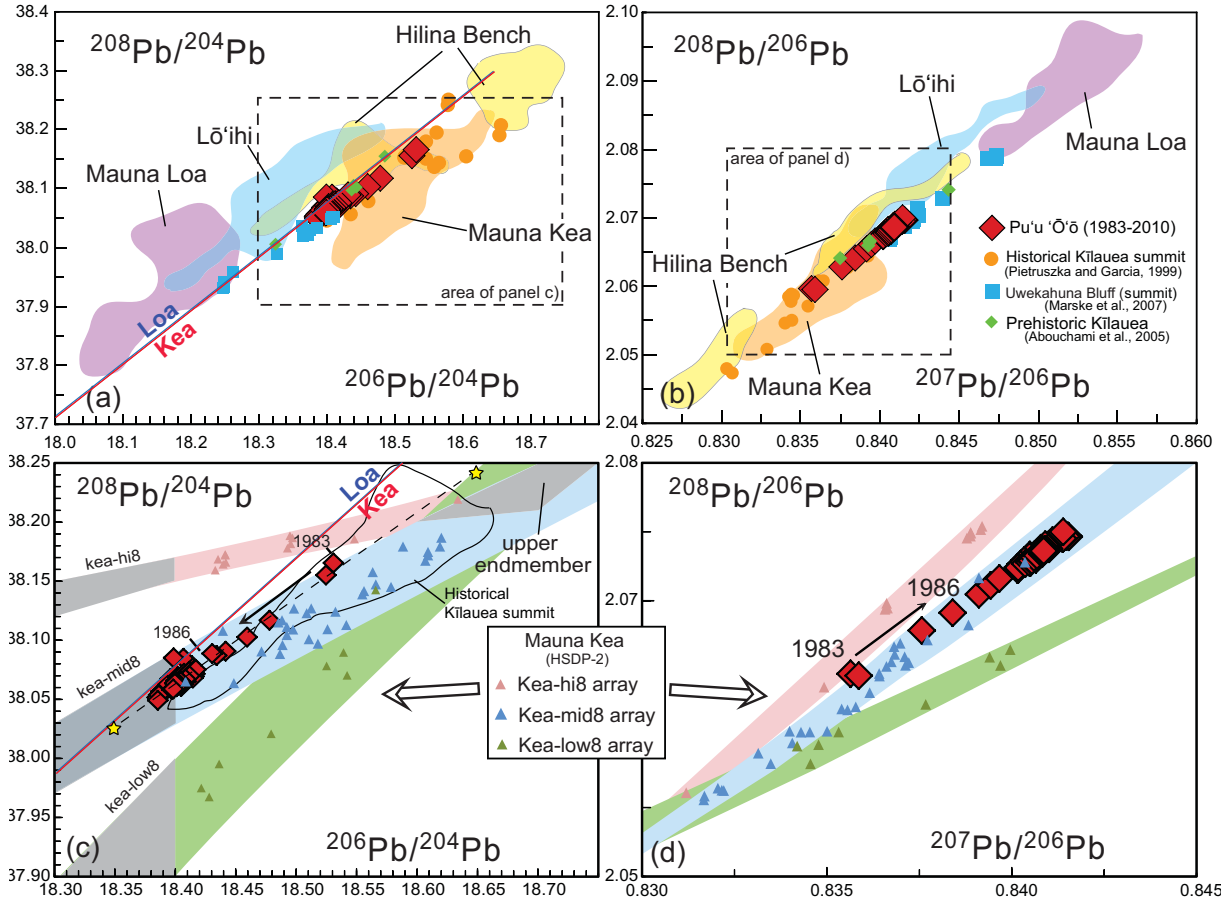

Figure 11. Pb isotopic compositions for Pu'u 'Ō'ō lavas compared to some other Hawaiian shield volcanoes. Top panels are different scales than bottom panels, shown by area of dashed boxes. Colored symbols are lavas from Kīlauea Volcano. Fields are for Mauna Loa, Lō'ihi, Mauna Kea, and submarine prehistoric Kīlauea (Hilina Bench; >40 ka). References for data sources are listed in the supporting information. Kea array end-members are from *Eisele et al.* [2003]. Dashed line with yellow stars in Figure 11c is a best fit line for Pu'u 'Ō'ō lavas from 1988 to 2010.

the chemical structure of the Hawaiian mantle plume, and the dynamics of melt transport and mixing within the mantle. Our new results show:

[36] 1. The Pu'u 'Ō'ō eruption is being supplied by new, compositionally variable, mantle-derived magma, which is being modified by various crustal processes including crystal fractionation (mainly olivine), magma mixing (during 1983–1984 and episode 54), and oxygen isotope exchange with or assimilation of altered Kīlauea rocks.

[37] 2. The episode 56 fissure lava has the highest $\delta^{18}O$ value (5.6‰) of any Pu'u 'Ō'ō lava and the highest MgO of any lava erupted since July 2000. Thus, it may be representative of the magma feeding this eruption as of June 2007. The episode 56 fissure was fed from an upper East Rift Zone dike rather than the shallow Pu'u 'Ō'ō reservoir. Coeval lavas erupted from the Pu'u 'Ō'ō vent have lower $\delta^{18}O$ values (5.3 ± 0.1‰) suggesting they were contaminated, probably in the shallow reservoir under the vent. Pu'u 'Ō'ō lavas show no correlation of $\delta^{18}O$ values with other geochemical parameters. For that reason, we suggest that the $\delta^{18}O$ ratios were lowered by oxygen exchange with or assimilation of altered Kīlauea wall rock.

[38] 3. Contrary to expectations, the dramatic increase in magma supply between 2003 and 2007 for the Pu'u 'Ō'ō eruption was not accompanied by higher MgO contents. Instead, lavas erupted during the 2003–2007 surge have lower MgO indicative of greater cooling of the magma prior to eruption, continuing the long-term trend for the eruption.

[39] 4. Rapid and remarkably systematic variations in Pb and Sr isotopic ratios are present in Pu'u

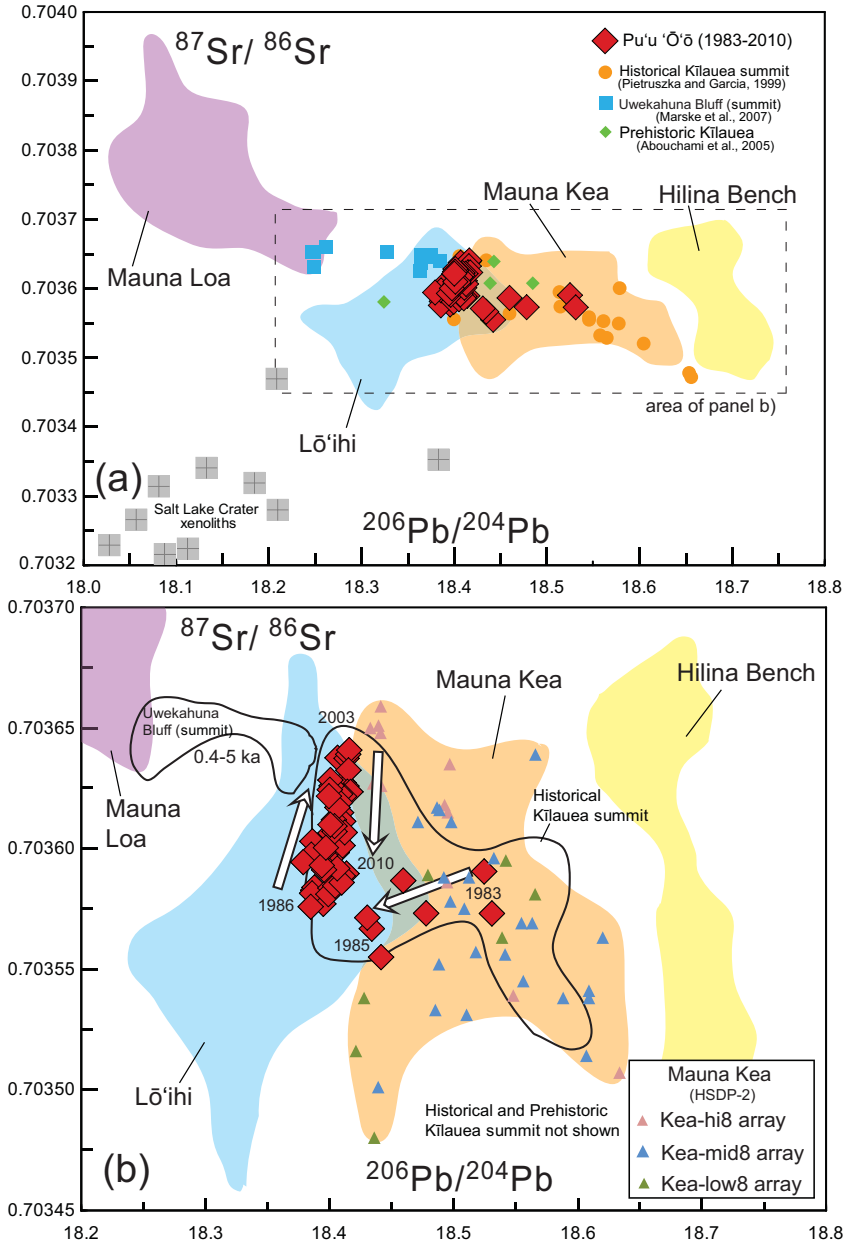

Figure 12. Plots of $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ for Pu'u 'Ō'ō lavas compared to some other Hawaiian shield volcanoes. Figure 12b Expanded scale of dashed box in Figure 12a. Colored symbols are lavas from Kīlauea Volcano. Fields are for Mauna Loa, Lō'ihi, Mauna Kea and submarine Kīlauea (Hilina Bench; >40 ka). References for data sources are listed in the supporting information.

'Ō'ō lavas. Two cycles of Pb isotopic ratio variation with ~10 year periods were found. These cycles may be related to extraction of melt from a source with a pattern of vertically oriented source heterogeneities, or thin strands. These strands may be ~1–3 km in diameter to explain the scale of isotopic variation for the Pu'u 'Ō'ō eruption.

[40] 5. The Pb isotopic variation of Pu'u 'Ō'ō lavas spans 25% of the range observed for the last 1000 years of Kīlauea summit lavas and 30% for ~300,000 years of shield volcanism for Mauna Kea volcano. There is considerable Pb and Sr isotopic overlap between Pu'u 'Ō'ō lavas and lavas from Mauna Kea and Lō'ihi volcanoes. However, the Pb-Sr isotopic trend for the later Pu'u 'Ō'ō lavas (1988–2010) is oblique to the array defined by Hawaiian shield lavas. Thus, each Hawaiian volcano appears to have an isotopically distinct source.

Acknowledgments

[41] We thank Jane Barling, Bruno Kieffer, and Vivian Lai for their assistance with analyses at PCIGR at UBC, Kyle Tanguichi and Adonara Murek for sample preparation and curation at the University of Hawai'i, and J. M. Rhodes for XRF analyses at University of Massachusetts. Claude Maerschalk assisted with Pb and Sr column chemistry for a subset of samples. Daniel Heaton provided assistance with several isotope analyses at San Diego State University. We appreciate reviews by Julie Prytulak, Joel Baker, and Christoph Beier. This research was supported by grants from the National Science Foundation to M. Garcia (EAR11–18741) and A. Pietruszka (EAR11–18738). This paper is SOEST Contribution No. 8939.

References

Abouchami, W., S. J. G. Galer, and A. W. Hofmann (2000), High precision lead isotope systematics of lavas from the Hawaiian Scientific Drilling Project, *Chem. Geol.*, *169*, 187–209, doi:10.1016/S0009–2541(00)00328-4.

Abouchami, W., A. W. Hofmann, S. J. G. Galer, F. A. Frey, J. Eisele, and M. Feigenson (2005), Lead isotopes reveal bilateral asymmetry and vertical continuity in the Hawaiian mantle plume, *Nature*, *434*, 851–856, doi:10.1038/nature03402.

Albarède, F., B. Luais, G. Fitton, M. Semet, E. Kaminski, B. G. J. Upton, P. Bachèlery, and J.-L. Cheminée (1997), The geochemical regimes of Piton de la Fournaise Volcano (Réunion) during the last 530,000 years, *J. Petrol.*, *38*, 171–201.

Blichert-Toft, J., and F. Albarède (2009), Mixing of isotopic heterogeneities in the Mauna Kea plume conduit, *Earth Planet. Sci. Lett.*, *282*, 190–200, doi:10.1016/j.epsl.2009.03.015.

Blichert-Toft, J., D. Weis, C. Maerschalk, A. Agranier, and F. Albarède (2003), Hawaiian hot spot dynamics as inferred from the Hf and Pb isotope evolution of Mauna Kea volcano, *Geochem. Geophys. Geosyst.*, *4*(2), 8704, doi:10.1029/2002GC000340.

Bryce, J. G., D. J. DePaolo, and J. C. Lassiter (2005), Geochemical structure of the Hawaiian plume: Sr, Nd, and Os isotopes in the 2.8 km HSDP-2 section of Mauna Kea volcano, *Geochem. Geophys. Geosyst.*, *6*, Q09G18, doi:10.1029/2004GC000809.

Caroff, M., R. C. Maury, P. Vidal, G. Guille, C. Dupuy, J. Cotten, H. Guillou, and P.-Y. Gillot (1995), Rapid temporal changes in ocean island basalt composition: Evidence from an 800 m deep drill hole in Eiao Shield (Marquesas), *J. Petrol.*, *36*(5), 1333–1365, doi:10.1093/petrology/36.5.1333.

Chen, C. Y., and F. A. Frey (1985), Trace element and isotopic geochemistry of lavas from Haleakala Volcano, east Maui, Hawai'i: Implications for the origin of Hawaiian basalts, *J. Geophys. Res.*, *90*, 8743–8768.

Chen, C.-Y., F. A. Frey, J. M. Rhodes, and R. M. Easton (1996), Temporal geochemical evolution of Kīlauea Volcano: Comparison of Hilina and Puna basalt, in *Earth Processes, Reading the Isotopic Code*, edited by A. Basu and S. R. Hart, pp. 161–181, AGU, Washington, D. C.

Cordier, C., M. Benoit, C. Hémond, J. Dyment, B. Le Gall, A. Briais, and M. Kitazawa (2010), Time scales of melt extraction revealed by distribution of lava composition across a ridge axis, *Geochem. Geophys. Geosyst.*, *11*, Q0AC06, doi:10.1029/2010gc003074.

DePaolo, D. J., and E. M. Stolper (1996), Models of Hawaiian volcano growth and plume structure: Implications from the Hawai'i Scientific Drilling Project, *J. Geophys. Res.*, *101*, 11,643–11,655.

Dvorak, J. J., and D. Dzurisin (1993), Variations in magma supply rate at Kīlauea Volcano, Hawai'i, *J. Geophys. Res.*, *98*, 22,255–22,268.

Eaton, J. P., and K. J. Murata (1960), How volcanoes grow [Hawai'i], *Science*, *132*, 925–938.

Eiler, J. M. (2001), Oxygen isotope variations of basaltic lavas and upper mantle rocks, *Rev. Mineral. Geochem.*, *43*(1), 319–364, doi:10.2138/gsrmg.43.1.319.

Eisele, J. R., W. Abouchami, S. J. G. Galer, and A. W. Hofmann (2003), The 320 kyr Pb isotope evolution of Mauna Kea lavas recorded in the HSDP-2 drill core, *Geochem. Geophys. Geosyst.*, *4*(5), 8710, doi:10.1029/2002GC000339.

Farnetani, C. G., and A. W. Hofmann (2009), Dynamics and internal structure of a lower mantle plume conduit, *Earth Planet. Sci. Lett.*, *282*(1–4), 314–322, doi:10.1016/j.epsl.2009.03.035.

Farnetani, C. G., and A. W. Hofmann (2010), Dynamics and internal structure of the Hawaiian plume, *Earth Planet. Sci. Lett.*, *295*, 231–240, doi:10.1016/j.epsl.2010.04.005.

Garcia, M. O., R. A. Ho, J. M. Rhodes, and E. W. Wolfe (1989), Petrologic constraints on rift-zone processes: Results from episode 1 of the Pu'u 'Ō'ō eruption of Kīlauea volcano, Hawai'i, *Bull. Volcanol.*, *52*, 81–96.

Garcia, M. O., J. M. Rhodes, E. W. Wolfe, G. E. Ulrich, and R. A. Ho (1992), Petrology of lavas from episodes 2–47 of the Pu'u 'Ō'ō eruption of Kīlauea Volcano, Hawai'i: Evaluation of magmatic processes, *Bull. Volcanol.*, *55*(1), 1–16.

Garcia, M. O., J. M. Rhodes, F. A. Trusdell, and A. J. Pietruszka (1996), Petrology of lavas from the Pu'u 'Ō'ō eruption of Kīlauea Volcano: III The Kupaianaha episode (1986–1992), *Bull. Volcanol.*, *58*, 359–379.

Garcia, M. O., E. Ito, J. M. Eiler, and A. J. Pietruszka (1998), Crustal contamination of Kīlauea Volcano magmas revealed by oxygen isotope analyses of glass and olivine from Pu'u 'Ō'ō eruption lavas, *J. Petrol.*, *39*, 803–817.

Garcia, M. O., A. J. Pietruszka, J. M. Rhodes, and K. Swanson (2000), Magmatic processes during the prolonged Pu'u 'Ō'ō eruption of Kīlauea Volcano, Hawai'i, *J. Petrol.*, *41*(7), 967–990.

Garcia, M. O., A. J. Pietruszka, and J. M. Rhodes (2003), A petrologic perspective of Kīlauea Volcano's summit magma reservoir, *J. Petrol.*, *44*(12), 2313–2339, doi:10.1093/petrology/egg079.

Garcia, M. O., E. Ito, and J. M. Eiler (2008), Oxygen isotope evidence for chemical interaction of Kīlauea historical magmas with basement rocks, *J. Petrol.*, *49*(4), 757–769, doi:10.1093/petrology/egm034.

Hanyu, T., J.-I. Kimura, M. Katakuse, A. T. Calvert, T. W. Sisson, and S. I. Nakai (2010), Source materials for inception stage Hawaiian magmas: Pb-He isotope variations for early Kīlauea, *Geochem. Geophys. Geosyst.*, *11*, Q0AC01, doi:10.1029/2009gc002760.

Harmon, R. S., and J. Hoefs (1995), Oxygen isotope heterogeneity of the mantle deduced from global ^{18}O systematics of basalts from different geotectonic settings, *Contrib. Mineral. Petrol.*, *120*(1), 95–114.

Hauri, E. H. (1996), Major-element variability in the Hawaiian mantle plume, *Nature*, *382*, 415–419.

Heliker, C., and T. N. Mattox (2003), The first two decades of the Pu'u 'Ō'ō -Kupaianaha eruption; chronology and selected bibliography, in *The Pu'u 'Ō'ō -Kupaianaha Eruption of Kīlauea Volcano, Hawai'i: The First 20 Years*, edited

by C. Heliker et al., pp. 1–28, U.S. Geol. Surv. Prof. Pap. 1676.

Hofmann, A. W., M. D. Feigenson, and I. Raczek (1984), Case studies on the orgin of basalt: III Petrogenesis of the Mauna Ulu eruption, Kīlauea, 1969–1971, *Contrib. Mineral. Petrol.*, *88*, 24–35.

Holcomb, R. T. (1987), Eruptive history and long-term behavior of Kīlauea Volcano, in *Volcanism in Hawai'i*, edited by R. W. Decker et al., pp. 261–350, U.S. Geol. Surv. Prof. Pap. 1350.

Jackson, M. G., D. Weis, and S. Huang (2012), Major element variations in Hawaiian shield lavas: Source features and perspectives from global ocean island basalt (OIB) systematics, *Geochem. Geophys. Geosyst.*, *13*, Q09009, doi:10.1029/2012GC004268.

Johnson, D. J., A. A. Eggers, and M. Bagnardi (2010), Shallow magma accumulation at Kīlauea Volcano, Hawai'i, revealed by microgravity surveys, *Geology 38*(12), 1139–1142, doi:10.1130/G31323.1.

Kimura, J.-I., T. W. Sisson, N. Nakano, M. L. Coombs, and P. W. Lipman (2006), Isotope geochemistry of early Kīlauea magmas from the submarine Hilina bench: The nature of the Hilina mantle component, *J. Volcanol. Geotherm. Res.*, *151*(1–3), 51–72, doi:10.1016/j.jvolgeores.2005.07.024.

Kurz, M. D., W. J. Jenkins, and S. R. Hart (1982), Helium isotopic systematics of oceanic islands and mantle heterogeneity, *Nature*, *297*, 43–47.

Macdonald, G. A., A. T. Abbott, and F. L. Peterson (1983), *Volcanoes in the Sea: The Geology of Hawai'i*, 517 pp., Univ. of Hawaii Press, Honolulu, Hawaii.

Maclennan, J. (2008), Lead isotope variability in olivine-hosted melt inclusions from Iceland, *Geochim. Cosmochim. Acta*, *72*(16), 4159–4176, doi:10.1016/j.gca.2008.05.034.

Marske, J. P., A. J. Pietruszka, D. Weis, M. O. Garcia, and J. M. Rhodes (2007), Rapid passage of a small-scale mantle heterogeneity through the melting regions of Kīlauea and Mauna Loa volcanoes, *Earth Planet. Sci. Lett.*, *259*, 34–50, doi:10.1016/j.epsl.2007.04.026.

Marske, J. P., M. O. Garcia, A. J. Pietruszka, J. M. Rhodes, and M. D. Norman (2008), Geochemical variations during Kīlauea's Pu'u 'Ō'ō eruption reveal a fine-scale mixture of mantle heterogeneities within the Hawaiian plume, *J. Petrol.*, *49*(7), 1297–1318, doi:10.1093/petrology/egn025.

Montgomery-Brown, E. K., D. K. Sinnett, P. S. M. Poland, T. Orr, H. Zebker, and A. Miklius (2010), Geodetic evidence for en echelon dike emplacement and concurrent slow slip during the June 2007 intrusion and eruption at Kīlauea volcano, Hawai'i, *J. Geophys. Res.*, *115*, B07405, doi:10.1029/2009JB006658.

Nobre Silva, I. G., D. Weis, and J. S. Scoates (2013), Isotopic systematics of the early Mauna Kea shield phase and insight into the deep mantle beneath the Pacific Ocean, *Geochem. Geophys. Geosyst.*, *14*(3), 659–676, doi:10.1029/2012GC004373.

Pietruszka, A. J., and M. O. Garcia (1999), A rapid fluctuation in the mantle source and melting history of Kīlauea Volcano inferred from the geochemistry of its historical summit lavas (1790–1982), *J. Petrol.*, *48*(8), 1321–1342.

Pietruszka, A. J., K. H. Rubin, and M. O. Garcia (2001), ^{226}Ra-^{230}Th-^{238}U disequilibria of historical Kīlauea lavas (1790–1982) and the dynamics of mantle melting within the Hawaiian plume, *Earth Planet. Sci. Lett.*, *186*, 15–31.

Pietruszka, A. J., E. H. Hauri, R. W. Carlson, and M. O. Garcia (2006), Remelting of recently depleted mantle within the Hawaiian plume inferred from the ^{226}Ra-^{230}Th-^{238}U disequilibria of Pu'u 'Ō'ō eruption lavas, *Earth Planet. Sci. Lett.*, *244*(1–2), 155–169, doi:10.1016/j.epsl.2006.01.039.

Pietruszka, A. J., E. H. Hauri, and J. Blichert-Toft (2009), Crustal contamination of mantle-derived magmas within Piton de la Fournaise Volcano, Reunion Island, *J. Petrol.*, *50*(4), 661–684, doi:10.1093/petrology/egp016.

Pietruszka, A. J., M. D. Norman, M. O. Garcia, J. P. Marske, and D. H. Burns (2013), Chemical heterogeneity in the Hawaiian mantle plume from the alteration and dehydration of recycled oceanic crust, *Earth Planet. Sci. Lett.*, *361*, 298–309, doi:10.1016/j.epsl.2012.10.030.

Poland, M., A. Miklius, T. Orr, A. J. Sutton, C. Thornber, and D. Wilson (2008), New episodes of volcanism at Kīlauea Volcano, Hawai'i, *Eos Trans. AGU*, *89*(5), 37–38, doi:10.1029/2008EO050001.

Poland, M. P., A. Miklius, A. J. Sutton, and C. R. Thornber (2012), A mantle-driven surge in magma supply to Kīlauea Volcano during 2003–2007, *Nat. Geosci.*, *5*, 295–300, doi:10.1038/NGEO1426.

Reiners, P. W. (2002), Temporal-compositional trends in intraplate basalt eruptions: Implications for mantle heterogeneity and melting processes, *Geochem. Geophys. Geosyst.*, *3*(2), 1011, doi:10.1029/2001GC000250.

Ren, Z.-y., T. Hanyu, T. Miyazaki, Q. Chang, H. Kawabata, T. Takahashi, Y. Hirahara, A. R. L. Nichols, and Y. Tatsumi (2009), Geochemical differences of the Hawaiian shield lavas: Implications for melting process in the heterogeneous Hawaiian plume, *J. Petrol.*, *50*(8), 1553–573, doi:10.1093/petrology/egp041.

Rhodes, J. M., and S. R. Hart (1995), Episodic trace element and isotopic variations in Mauna Loa lavas: Implications for magma and plume dynamics, in *Mauna Loa Revealed: Structure, Composition, History and Hazards*, edited by J. M. Rhodes and J. P. Lockwood, pp. 263–288, AGU, Washington, D. C.

Rhodes, J. M., and M. J. Vollinger (2004), Composition of basaltic lavas sampled by phase-2 of the Hawai'i Scientific Drilling Project: Geochemical stratigraphy and magma types, *Geochem. Geophys. Geosyst.*, *5*, Q03G13, doi:10.1029/2002GC000434.

Rhodes, J. M., S. Huang, F. A. Frey, M. Pringle, and G. Xu (2012), Compositional diversity of Mauna Kea shield lavas recovered by the Hawai'i Scientific Drilling Project: Inferences on source lithology, magma supply, and the role of multiple volcanoes, *Geochem. Geophys. Geosyst.*, *13*, Q03014, doi:10.1029/2011GC003812.

Ryan, M. P. (1987), Elasticity and contractancy of Hawaiian olivine tholeiite and its role in the stability and structural evolution of subcaldera magma reservoirs and rift systems, in *Volcanism in Hawai'i*, edited by R. W. Decker et al., pp. 1395–1448, U.S. Geol. Surv. Prof. Pap. 1350.

Shamberger, P. J., and M. O. Garcia (2007), Geochemical modeling of magma mixing and magma reservoir volumes during early episodes of Kīlauea Volcano's Pu'u 'Ō'ō eruption, *Bull. Volcanol.*, *69*, 345–352, doi:10.1007/s00445-006-0074-5.

Sims, K. W. W., M. T. Murrell, D. J. DePaolo, W. S. Baldridge, S. J. Goldstein, D. Clague, and M. Jull (1999), Porosity of the melting zone and variations in the solid mantle upwelling rate beneath Hawai'i: Inferences from ^{238}U-^{230}Th-^{226}Ra and ^{235}U-^{231}Pa disequilibria, *Geochim. Cosmochim. Acta*, *63*(23), 4119–4138.

Sobolev, A. V., A. W. Hofmann, S. Sobolev, and I. K. Nikogosian (2005), An olivine-free mantle source of Hawaiian shield basalts, *Nature*, *434*, 590–595.

Sutton, J. A., T. Elias, and J. Kauahikaua (2003), Lava-effusion rates for the Pu'u 'Ō'ō -Kupaianaha eruption derived from SO_2 emissions and very low frequency (VLF) measurements, in *The Pu'u 'Ō'ō -Kupaianaha Eruption of Kīlauea Volcano, Hawai'i: The First 20 Years*, edited by C. Heliker et al., pp. 137–148, U.S. Geol. Surv. Prof. Pap. 1676.

Thornber, C. R. (2003), Magma-reservoir processes revealed by geochemistry of the Pu'u 'Ō'ō-Kupaianaha eruption, in *The Pu'u 'Ō'ō -Kupaianaha Eruption of Kīlauea Volcano, Hawai'i: The First 20 Years*, edited by C. Heliker et al., pp. 121–136, U.S. Geol. Surv. Prof. Pap. 1676.

Thornber, C. R., C. Heliker, D. R. Sherrod, J. P. Kauahikaua, A. Miklius, P. G. Okubo, F. A. Trusdell, J. R. Budahn, W. I. Ridley, and G. P. Meeker (2003), Kīlauea East Rift Zone magmatism: An episode 54 perspective, *J. Petrol.*, *44*(9), 1525–1559, doi:10.1093/petrology/egg048.

Tilling, R. I., and J. J. Dvorak (1993), Anatomy of a basaltic volcano, *Nature*, *363*, 125–133.

Vlastélic, I., T. Staudacher, and M. Semet (2005), Rapid change of lava composition from 1998 to 2002 at Piton de la Fournaise (Réunion) inferred from Pb isotopes and trace elements: Evidence for variable crustal contamination, *J. Petrol.*, *46*(1), 79–107, doi:10.1093/petrology/egh062.

Vlastélic, I., A. Peltier, and T. Staudacher (2007), Short-term (1998–2006) fluctuations of Pb isotopes at Piton de la Fournaise volcano (Réunion Island): Origins and constraints on the size and shape of the magma reservoir, *Chem. Geol.*, *244*, 202–220, doi:10.1016/j.chemgeo.2007.06.015.

Watson, S., and D. McKenzie (1991), Melt generation by plumes: A study of Hawaiian volcanism, *J. Petrol.*, *32*(3), 501–537.

Weis, D., M. O. Garcia, J. M. Rhodes, A. M. Jellinek, and J. S. Scoates (2011), Role of the deep mantle in generating the compositional asymmetry of the Hawaiian mantle plume, *Nat. Geosci.*, *4*, 831–838, doi:10.1038/ngeo1328.

Wolfe, E. W., M. O. Garcia, D. B. Jackson, R. Y. Koyanagi, C. A. Neal, and A. T. Okamura (1987), The Pu'u 'Ō'ō eruption of Kīlauea Volcano, episodes 1–20, January 3, 1983 to June 8, 1984, in *Volcanism in Hawai'i*, edited by R. W. Decker et al., pp. 471–508, U.S. Geol. Surv. Prof. Pap. 1350.

Wright, T. L. (1971), Chemistry of Kīlauea and Mauna Loa lava in space and time, *U.S. Geol. Surv. Prof. Pap.*, *735*, 1–45.